

## Article

# Spatio-Temporal Evolution of Surface Urban Heat Island Distribution in Mountainous Urban Areas Based on Local Climate Zones: A Case Study of Tongren, China

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## Abstract

Against the backdrop of climate change and the accelerated process of urbanization, the risks of extreme weather and natural disasters that cities are facing are increasing day by day. Based on the framework of the local climate zone (LCZ), this paper studies the spatio-temporal evolution of the urban surface morphology and the heat island effect of Tongren City. Using the comprehensive mapping technology of remote sensing and GIS, combined with the inversion of surface temperature, the distribution of LCZs and the changes in heat island intensity were analyzed. The results show that: (1) The net increase in forest coverage area leads to a decrease in shrub and grassland area, resulting in an ecological deficit. (2) The built-up area expands along transportation routes, and industrial areas encroach upon natural space. (3) The urban heat island pattern has evolved from a single core to multiple cores and eventually becomes fragmented. (4) Among the seasonal dominant driving factors of urban heat islands, the impervious water surface is in summer, the terrain roughness and building height are in winter, and the building density is in spring and autumn. These findings provide feasible insights into mitigating the heat island effect through climate-sensitive urban planning.

**Keywords:** classification of local climate zones; land surface temperature; thermal environment effect; karst mountain city



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## 1. Introduction

Global warming has emerged as a pivotal environmental challenge confronting contemporary human societal development [1]. Projections indicate that by 2050, over two-thirds of the global population will reside in urban areas, significantly heightening exposure to the adverse effects of climate change [2]. The global warming trend persists. As the largest developing country, China faces heightened scrutiny owing to its pronounced vulnerability and substantial impact significance. The transformation of urban spatial structures, driven by the rapid expansion of built-up areas during urbanization, is accompanied not only by increased local temperatures but also by exacerbated urban heat island effects [3]. The urban heat island effect refers to the phenomenon where the temperature in the city center is significantly higher than the natural environment of the surrounding suburbs. It is mainly caused by factors such as changes in the urban underlying surface and anthropogenic heat emissions. Driven by China's 'Western Development' policy, accelerated urbanization in karst mountain cities has induced substantial alterations to urban

surface characteristics, catalyzing distinct transformations in their thermal environmental spatial patterns [4,5]. Although existing research has yielded significant insights, studies on the regional specificity of thermal environments in karst mountain cities remain inadequate. Addressing this gap is imperative: investigating urban areas characterized by later-onset urbanization and complex topographies not only mitigates urban heat island effects but also holds the key to achieving sustainable development for mountain cities across China and globally.

Current research on the urban heat island (UHI) effect remains hindered by the absence of standardized intensity metrics. Prevailing studies predominantly adopt an oversimplified urban–rural dichotomy [6], while city-scale analyses frequently neglect intra-urban spatial heterogeneity and surface cover variations. This methodological limitation critically impedes the translation of findings into actionable strategies for optimizing localized spatial configurations. To describe the complex urban space more precisely and multi-dimensionally, an increasing number of scholars have conducted research using the theoretical framework of the local climate zone classification system (LCZ) proposed by Stewart et al. in 2012. [7]. Prevailing scholarship on LCZ-based urban heat island studies primarily focuses on: (i) LCZ data acquisition methodologies [8], (ii) univariate correlations with UHI intensity [9], and (iii) urban morphological classification and future scenario simulations [7,10]. Nevertheless, systematic investigations examining interaction mechanisms between urban spatial form parameters and LCZ-scale thermal environments remain inadequately explored [9]. Dominant LCZ classification approaches encompass remote sensing, ArcGIS-based, and integrated mapping methodologies. However, remote sensing-driven LCZ mapping exhibits limitations in land cover classification accuracy [11], while ArcGIS-dependent methods face persistent challenges in acquiring comprehensive socio-economic datasets [8]. To mitigate these constraints, hybrid mapping techniques synergistically combining both approaches have emerged as a promising alternative [12]. Conventional LCZ studies predominantly utilize single-temporal data, constraining their applicability to dynamic urban processes [13]. Concurrently, prevailing mapping techniques insufficiently address longitudinal consistency in historical LCZ classification, compromising comparative temporal analyses [14]. Empirical evidence confirms land surface temperature (LST) as a reliable discriminator of LCZ types [15,16]. In examining machine learning (ML) impacts on urban morphology–LST/SUHII relationships, models including Random Forest (RF) [16], Boosted Regression Trees (BRT) [17], Artificial Neural Networks (ANN) [18], and Convolutional Neural Networks (CNN) [19] feature prominently. The Random Forest (RF) model permits rigorous quantification and hierarchical ranking of feature variables' predictive significance while serving as a robust regression tool capable of modeling complex nonlinear relationships [20]. Furthermore, we have noticed that the application of local climate zones (LCZ) in complex terrain areas such as mountainous regions in southwest China (like Chongqing) has made certain progress [21]. However, most studies have focused on scales such as economically developed regions, megacities, or urban agglomerations [22,23]. Research on the urban heat island effect in karst mountainous areas with special geographical features and underdevelopment is still not in-depth enough and lacks systematic understanding.

Tongren City is a representative karst mountain city in southwest China. It lacks alluvial plains and has distinct topographic features [24]. It is a typical area where social and economic constraints persist in underdeveloped regions of China [25]. Due to its climate type, regional characteristics, development stage, and work foundation, Tongren was selected as one of the first 39 pilot cities for climate-resilient urban construction in China

in 2024 [26]. China attaches great importance to the climate construction requirements of Tongren. Climate construction has become a key point in current urban construction, which also makes the climate issue of Tongren an object that China urgently needs to study at present. Meanwhile, its unique deep-cut canyon terrain and the band-like distribution pattern of cities along mountains and rivers provide an extremely unique and ideal natural laboratory for studying the interaction between terrain, heat, and urban forms and their impact on the thermal environment. This forms a sharp contrast with cities developed on flat terrain and can better reveal the unique mechanism of the heat island in mountainous cities.

Therefore, based on the local climate zone (LCZ) theory, this study takes Tongren City as the research object to explore the spatio-temporal evolution characteristics of the surface heat island intensity and LCZ in Tongren City. Firstly, we collected and analyzed multi-source data of Tongren from 2016 to 2023, established the LCZ classification system of Tongren City, and generated multi-time series LCZ zoning maps and LST distribution maps. Secondly, we analyzed the changing trends and interannual differences in the distribution of surface urban heat island characteristics during the same period, and we compared the differences in heat island intensity indices among different LCZ types. Finally, the RF model was utilized to analyze the relative importance of each variable factor to the heat island intensity. The research results can provide scientific basis for urban planning departments, optimize urban climate from the perspective of local climate zones, and offer suggestions for mitigating the heat island effect in the construction of climate-suitable cities in China and other underdeveloped mountainous cities around the world.

## 2. Methods and Materials

### 2.1. Overview of the Research Object

Tongren City is situated in northeastern Guizhou Province, within a transitional zone between the Yunnan-Guizhou Plateau and the Xiangxi Hilly Region of southwestern China [27]. Its geographical coordinates span 107°45′–109°39′ E longitude and 27°07′–29°05′ N latitude [28]. The city has undergone rapid development in recent years, with its permanent resident population reaching 3.2137 million and the urbanization rate attaining 48% by the end of 2023 [29]. Tongren features a predominantly mountainous terrain with pronounced undulation, where mountainous regions constitute 67.8% of the total urban area. Karst landscapes span 10,965 km<sup>2</sup>, accounting for approximately 61% of the city's land [30]. Tongren experiences a subtropical monsoon humid climate characterized by significant spatial heterogeneity in weather patterns owing to its complex topography [27,30]. Tongren's tourism industry, functioning as a leading economic sector, exhibits significant sensitivity to seasonal climatic variations due to the region's distinctive geographical setting and rich ecological endowments [31]. The annual average temperature ranges from 13.8 to 17.8 °C, with record highs peaking at 42 °C in August and extreme lows reaching −9.4 °C in January [32]. During summer (June–August), prolonged rainless periods result in a summer drought probability of 84–94% across Tongren, averaging approximately 88% [33]. This climatic profile renders Tongren highly suitable for urban heat island (UHI) effect studies. Consequently, the central urban area—covering 344.75 km<sup>2</sup>—was designated as the focal research zone (Figure 1).

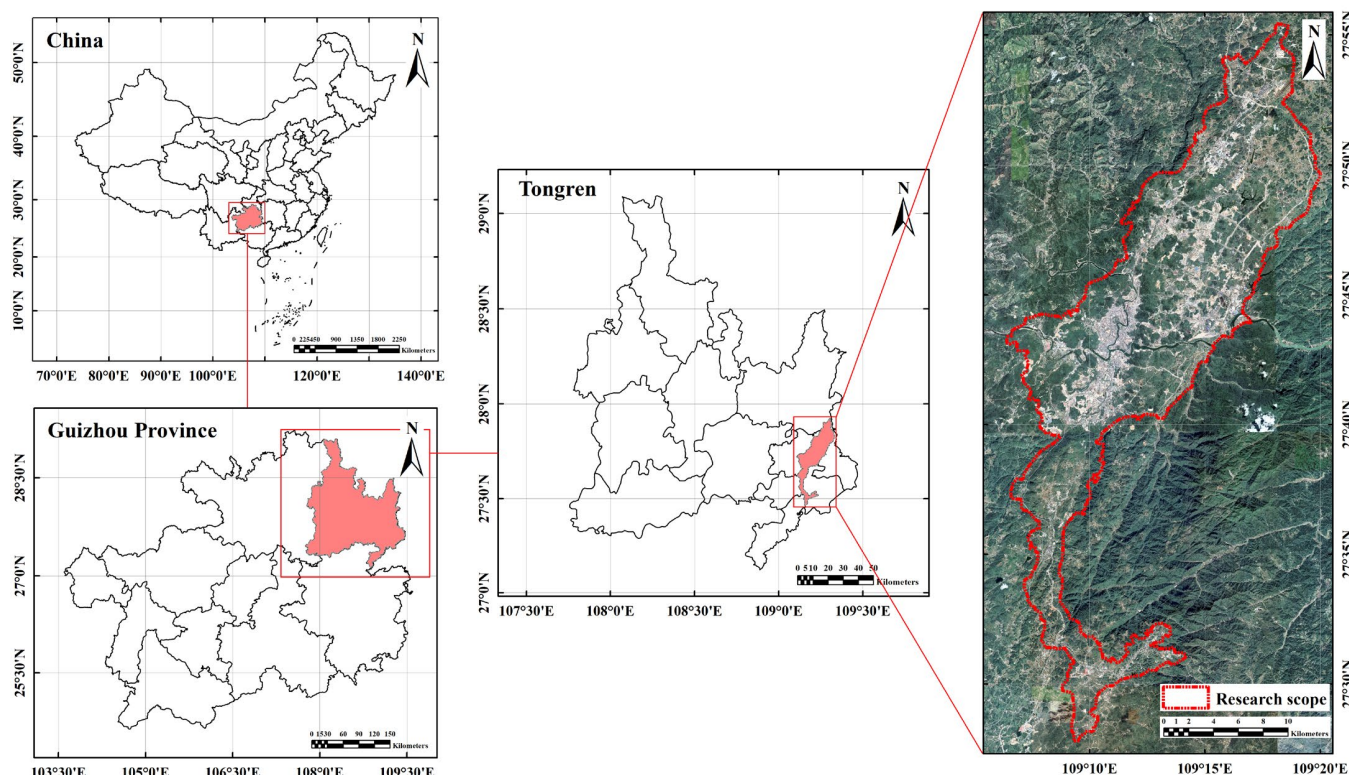


**Figure 1.** Geographical location of the research subjects.

## 2.2. Data Source

This study employed two primary data categories for analysis: remote sensing imagery and geospatial datasets, as outlined in Table 1. Specifically, Landsat 7 and Landsat 8–9 scenes with a 30 m resolution were sourced from the USGS Earth Explorer platform (<https://earthexplorer.usgs.gov/>; accessed on 1 August 2025) to facilitate surface temperature inversion. A total of 12 sets of remote sensing data with cloud cover less than 10 were collected for the spring (from March to May), summer (from June to August), autumn (from September to November), and winter (from December to February of the following year) of 2016, 2020, and 2023. (Images with cloud coverage higher than 10% were identified and excluded from the analysis using the official cloud mask product.) Additionally, architectural morphology data for the same years were extracted via the AMap API (<https://lbs.amap.com/>; accessed on 2 August 2025), while land cover classifications at 30 m resolution originated from the CLCD dataset [34] (<https://zenodo.org/records/12779975>; accessed on 3 August 2025), produced by Wuhan University researchers, to support detailed local climate zone mapping and ensure comprehensive environmental characterization.

**Table 1.** Data sources and related parameters.

| Data Type                                        | Image ID                                 | Date           | Season | Resolution /m                                                               | Land Cloud Cover | Source                                                                                                               |
|--------------------------------------------------|------------------------------------------|----------------|--------|-----------------------------------------------------------------------------|------------------|----------------------------------------------------------------------------------------------------------------------|
| Landsat 8–9 OLI/TIRS<br>C2L2/Landsat 7 ETM+ C2L1 | LC08_L2SP_125041_20160416_20200907_02_T1 | 16 April 2016  | Spring | Multispectral band 30,<br>thermal infrared band 30                          | 21.66            | USGS ( <a href="https://earthexplorer.usgs.gov/">https://earthexplorer.usgs.gov/</a> ;<br>accessed on 1 August 2025) |
|                                                  | LC08_L2SP_125041_20200427_20200822_02_T1 | 27 April 2020  |        | Multispectral band 30,<br>thermal infrared band 30                          | 0.02             |                                                                                                                      |
|                                                  | LE07_L1TP_125041_20230430_20230526_02_T1 | 30 April 2023  |        | Panchromatic band 15,<br>multispectral band 30,<br>thermal infrared band 30 | 0.00             |                                                                                                                      |
|                                                  | LC08_L2SP_126041_20160829_20200906_02_T1 | 29 August 2016 | Summer | Multispectral band 30,<br>thermal infrared band 30                          | 0.08             |                                                                                                                      |
|                                                  | LC08_L2SP_126041_20200824_20200905_02_T1 | 24 August 2020 |        | Multispectral band 30,<br>thermal infrared band 30                          | 67.57            |                                                                                                                      |
|                                                  | LC08_L2SP_125041_20230607_20230614_02_T1 | 7 June 2023    |        | Multispectral band 30,<br>thermal infrared band 30                          | 11.80            |                                                                                                                      |

Table 1. Cont.

| Data Type                                        | Image ID                                 | Date              | Season | Resolution /m                                                               | Land Cloud Cover | Source                                                                                                                                             |
|--------------------------------------------------|------------------------------------------|-------------------|--------|-----------------------------------------------------------------------------|------------------|----------------------------------------------------------------------------------------------------------------------------------------------------|
| Landsat 8–9 OLI/TIRS<br>C2L2/Landsat 7 ETM+ C2L1 | LE07_L1TP_126041_20160922_20200902_02_T1 | 22 September 2016 | Autumn | Panchromatic band 15,<br>multispectral band 30,<br>thermal infrared band 30 | 57.00            | USGS ( <a href="https://earthexplorer.usgs.gov/">https://earthexplorer.usgs.gov/</a> ;<br>accessed on 1 August 2025)                               |
|                                                  | LC08_L2SP_126041_20201112_20210317_02_T1 | 12 November 2020  |        | Multispectral band 30,<br>thermal infrared band 30                          | 0.01             |                                                                                                                                                    |
|                                                  | LC09_L2SP_125041_20231021_20231024_02_T1 | 21 October 2023   |        | Multispectral band 30,<br>thermal infrared band 30                          | 0.88             |                                                                                                                                                    |
|                                                  | LE07_L1TP_126041_20170213_20200901_02_T1 | 13 February 2017  | Winter | Panchromatic band 15,<br>multispectral band 30,<br>thermal infrared band 30 | 26.00            |                                                                                                                                                    |
|                                                  | LC08_L2SP_126041_20210115_20210308_02_T1 | 15 January 2021   |        | Multispectral band 30,<br>thermal infrared band 30                          | 0.38             |                                                                                                                                                    |
|                                                  | LC08_L2SP_126041_20231223_20240103_02_T1 | 23 December 2023  |        | Multispectral band 30,<br>thermal infrared band 30                          | 4.34             |                                                                                                                                                    |
| Building vector data                             | –                                        | 2016              | –      | –                                                                           | –                | Amap ( <a href="https://lbs.amap.com/">https://lbs.amap.com/</a> ;<br>accessed on 2 August 2025)                                                   |
|                                                  | –                                        | 2020              | –      | –                                                                           | –                |                                                                                                                                                    |
|                                                  | –                                        | 2023              | –      | –                                                                           | –                |                                                                                                                                                    |
| Land cover data                                  | –                                        | 2016              | –      | 30                                                                          | –                | Wuhan university, China<br>( <a href="https://zenodo.org/records/12779975">https://zenodo.org/records/12779975</a> ;<br>accessed on 3 August 2025) |
|                                                  | –                                        | 2020              | –      | 30                                                                          | –                |                                                                                                                                                    |
|                                                  | –                                        | 2023              | –      | 30                                                                          | –                |                                                                                                                                                    |

### 2.3. Research Methods

#### 2.3.1. Local Climate Zone Classification Method

##### (1) Selection of LCZ Partition Grid Scale

Grid scale critically influences thermal environment studies [35], with Oke’s research [36] establishing that optimal Local Climate Zone (LCZ) spatial resolution requires a minimum diameter of 400–1000 m following scale effect analysis. Given variations in urban architectural morphology, cities exhibit distinct LCZ resolution requirements [37]. Consequently, this study employs the ordinary kriging model—a geostatistical method for spatial structure modeling and feature analysis—to perform semi-variogram analysis, defined by the following formulas:

$$\text{Semivariogram}(h) = 0.5 \times \frac{\sum [Z(x_i) - Z(x_i + h)]^2}{N(h)} \quad (1)$$

In this formulation, the semi-variogram function  $\gamma(h)$  quantifies spatial autocorrelation by measuring value disparities between sample points separated by distance  $h$ , where  $Z(x)$  denotes the observed value at location  $x$ ,  $Z(x + h)$  signifies the sample value at a position offset by  $h$ , and  $N(h)$  is defined as the count of sample pairs within distance  $h$ .

##### (2) Selection of LCZ Parameters

To accurately depict the unique three-dimensional spatial structure of mountainous cities and its impact on the thermal environment, under the guidance of the local climate zoning (LCZ) framework, this study aims to explore multiple dimensions such as two-dimensional planar layout, three-dimensional structure, and thermal properties of the underlying surface. This study also aims to comprehensively capture the complexity of the interaction between terrain and artificial buildings in mountainous cities, thereby laying a scientific foundation for subsequent microclimate analysis. This study classifies LCZ parameters into two categories: surface coverage indicators (permeable surface fraction (PSF), impermeable surface fraction (ISF), and terrain roughness grade ( $Z_0$ )) and architectural morphology indicators (sky view factor (SVF), mean building height ( $\overline{BH}$ ), building height standard deviation (HSD), building surface fraction (BSF), and floor area ratio (FAR)). Comprehensive definitions of these metrics are provided in Table 2. These parameters are the core characteristic indicators for determining the LCZ type of each grid. The values of these seven parameters were calculated for each analysis grid in the GIS platform. These calculated parameter values constitute the basic data matrix for the subsequent LCZ classification.

**Table 2.** LCZ parameters selected in this study and related explanations.

| Parameter          | Description     | Formula                                                                                                                                                                                                                                                                                                                           |
|--------------------|-----------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Land cover         | PSF [16]        | The proportion of the permeable surface area of the grid.<br>$PSF = PSA / A_i$ where PSA is the pervious surface area, and $A_i$ is the grid area of grid number $i$ .                                                                                                                                                            |
|                    | ISF [16]        | The proportion of the impermeable surface area of the grid.<br>$ISF = ISA / A_i$ where ISA is impervious surface area, and $A_i$ is the grid area of grid number $i$ .                                                                                                                                                            |
|                    | $Z_0$ [38]      | Describe the roughness length of the terrain surface (building geometry and land cover).<br>The roughness length is classified according to the classification system proposed by Davenport et al.                                                                                                                                |
|                    | SVF [39,40]     | A part of the hemisphere covered by the sky.<br>$\psi_{SVF} = 1 - \sum \sin^2 \beta_i \left( \frac{\alpha_i}{360} \right)$ where $\alpha_i$ is the azimuth angle, and $\beta_i$ is the maximum tilt angle along the pixel direction of the obstruction.                                                                           |
| Architectural form | $\overline{BH}$ | The weighted average height of the grid building.<br>$\overline{BH} = \sum_{i=1}^n H_i W_i$ where $i$ is the building number, $n$ is the total number of buildings in the grid, $H$ is the building height, and $W_i$ is the weight value of the total building area of building number $i$ in the grid area.                     |
|                    | HSD [16]        | The degree of variation in the building height of the grid.<br>$HSD = \sqrt{\frac{\sum_{i=1}^n (H_i - \bar{H})^2}{n-1}}$ where $i$ is the building number, $n$ is the total number of buildings in the grid, $H$ is the building height and $\bar{H}$ is the average building height.                                             |
|                    | BSF [41]        | The ratio of the building's floor area to the total area of the grid.<br>$BSF = \sum_{i=1}^n A_{arc} / A_j$ where $i$ is the building number, $A_{arc}$ is the footprint area of the $i$ building, $j$ is the grid number, and $A_j$ is the grid area of grid number $j$ .                                                        |
|                    | FAR [42]        | The ratio of the building's floor area to the total area of the grid.<br>$FAR = \sum_{i=1}^n A_{arc} F / A_j$ where $i$ is the building number, $A_{arc}$ is the footprint area of the $i$ building, $F$ is the number of floors of building number $i$ , $j$ is the grid number, and $A_j$ is the grid area of grid number $j$ . |

### (3) The Main Classification Process of LCZ

Local climate zone (LCZ) classification primarily employs remote sensing (RS), geographic information systems (GIS), or integrated RS–GIS approaches. This study adopts the integrated RS–GIS methodology, utilizing the CLCD dataset and RS imagery to identify land cover types while applying GIS tools for building classification. The entire workflow was executed within ArcGIS 10.8, leveraging the Raster Calculator and related tools. Key steps included: (1) preprocessing building and land cover data to establish a unified geodatabase; (2) calculating LCZ parameters using Table 2 formulas; (3) generating LCZ-scale grids for spatial overlay analysis; and (4) determining final LCZ categories per grid based on derived parametric thresholds. The final output of this process is the LCZ spatial distribution map and the corresponding attribute data table, which are used for subsequent evolution analysis and correlation analysis with heat island intensity.

### (4) LCZ Internal Type Conversion

To characterize the spatio-temporal evolution of local climate zone (LCZ) types in the study area, this study employed an LCZ transition matrix for change detection analysis. This approach quantifies areal shifts between LCZ categories across defined temporal intervals, precisely capturing the areal extent of each LCZ type per period while revealing inter-category conversion dynamics. Consequently, it facilitates rigorous quantification of transitional magnitudes among LCZ types during the study timeframe, thereby elucidating their evolutionary trajectories [43]. The results of this change detection and analysis will be presented in the form of a “LCZ Transition Matrix” table.

$$S_{ij} = \begin{bmatrix} S_{11} & S_{12} & \dots & S_{1G} \\ S_{21} & S_{22} & \dots & S_{2G} \\ \vdots & \vdots & \ddots & \vdots \\ S_{G1} & S_{G2} & \dots & S_{GG} \end{bmatrix} \quad (2)$$

Within the transition matrix framework, indices  $i$  and  $j$  denote local climate zone (LCZ) type codes for the initial and subsequent phases, respectively. The variable  $S$  quantifies

the areal transition magnitude from LCZ type  $i$  to type  $j$ , formally expressed as:  $S_{ij}$  = [areal conversion from type  $i$  to  $j$ ].

### 2.3.2. Surface Temperature Inversion Method

December 2020 saw the official release of the Landsat Collection 2 Level 2 (LC2L2) dataset by the United States Geological Survey (USGS), marking the inaugural provision of a surface temperature (LST) product derived from thermal infrared remote sensing inversion [44]. The LC2L2 LST data represent preprocessed secondary products incorporating geometric correction, radiometric calibration, and atmospheric correction, enabling direct analytical application. The specific algorithms for Landsat 8–9 are defined by the Landsat Science Team as follows [45]:

$$LST_{C2L2} = 0.00341802 \times DN + 149 - 273.15 \quad (3)$$

Here,  $LST_{C2L2}$  denotes land surface temperature in degrees Celsius ( $^{\circ}\text{C}$ ), while DN signifies the digital number (DN) value of Band 10 within the  $LST_{C2L2}$  product's thermal infrared data layer.

Traditional methods for land surface temperature (LST) inversion primarily encompass radiative transfer models, single-channel algorithms, and split-window algorithms [46]. Among these, the single-channel approach demonstrates superior accuracy and adaptability [47]. Although NASA's discontinued web service currently impedes direct access to atmospheric profile parameters, atmospheric reanalysis data can be leveraged to drive locally executed radiative transfer models, thereby deriving requisite atmospheric parameters for single-channel algorithm implementation [48,49]. Since the Landsat 7 C2L1 product does not include the surface temperature product, this study adopts the single-channel algorithm to perform surface temperature inversion for it. The main processes include radiometric calibration, specific emissivity estimation, atmospheric correction, projection conversion, study area trimming, and cloud removal. Its formula is as follows:

$$T_s = \frac{[a(1 - C - D) + (b(1 - C - D) + C + D)T_b - DT_a]}{C} \quad (4)$$

In this algorithm,  $T_s$  denotes the inverted land surface temperature ( $^{\circ}\text{C}$ ),  $T_b$  represents the brightness temperature of Landsat 7 ETM+ Band 6 (thermal infrared band), and  $T_a$  signifies the mean atmospheric effective temperature. Constants  $a$  and  $b$  are predefined coefficients for ETM+ Band 6 within specific temperature ranges, with values  $a = -67.355351$  and  $b = 0.458606$ . Intermediate variables  $C$  and  $D$  are functions of atmospheric transmittance and surface emissivity.

In this study, the corresponding algorithms mentioned above were used to invert the surface temperature (LST) of each period of remote sensing images, and finally, the raster charts of surface temperature in the study area for each period were generated. These temperature data are the core input data for the subsequent calculation of the heat island intensity.

### 2.3.3. Heat Island Intensity Calculation Method

The urban heat island intensity (UHII) calculation adopts LCZ-D (low vegetation) as the reference class, following the local climate zone (LCZ) framework established by Stewart and Oke [7]. This method quantifies thermal differentials relative to LCZ-D across all LCZ types. Given Tongren's urban characteristics, LCZ-C (shrubs) and LCZ-D were consolidated into a composite class LCZ-CD. These results will be summarized into

corresponding graphs and tables for comparative analysis of the thermal environmental effects of different LCZ types. The UHII is computed as:

$$\text{SUHII}_i = \text{LST}_{\text{LCZ}-i} - \text{LST}_{\text{LCZ}-\text{CD}} \quad (5)$$

Here,  $\text{SUHII}_i$  denotes the surface urban heat island intensity ( $^{\circ}\text{C}$ ),  $\text{LST}_{\text{LCZ}-i}$  represents the land surface temperature ( $^{\circ}\text{C}$ ) of each LCZ type, and  $\text{LST}_{\text{LCZ}-\text{CD}}$  signifies the spatially averaged reference temperature ( $^{\circ}\text{C}$ ) across the study area.

### 2.3.4. Random Forest Regression Model Algorithm

This study employed the Random Forest (RF) algorithm to quantify the relative importance of driving factors on surface urban heat island intensity (SUHII). The RF regression model integrates multiple decision trees, each trained via bootstrap sampling with random feature and data subsets [50]. The ensemble prediction  $\text{RF}(X)$  is derived by averaging outputs from all constituent decision trees  $T_n(X)$ , formalized as:

$$\text{RF}(X) = \frac{1}{n} \sum_{i=1}^n T_i(X) \quad (6)$$

In this formulation,  $\text{RF}(X)$  denotes the ensemble prediction of the Random Forest for feature vector  $X$ ,  $T_i(X)$  represents the output of the  $i$ -th decision tree, and  $n$  signifies the total number of trees in the ensemble model.

## 3. Results and Analysis

### 3.1. Development of a Local Climate Zone Classification Framework for Tongren City

#### 3.1.1. Spatial Resolution Sensitivity Analysis in LCZ Mapping Grid Scales

Figure 2 shows the analysis results, where the semi-variance exhibits a significant upward trend with increasing distance. Data comparison between 2016 and 2023 indicates that the semi-variance stabilizes near the 400 m mark, suggesting strong spatial autocorrelation within this scale range. Meanwhile, considering the complex mountainous terrain and fragmented plots in the study area, this scale can achieve the best balance between capturing microclimate variations and ensuring the statistical sample size. If the scale is too small, the noise will be excessive; if it is too large, the key terrain and land use details will be smoothed out. Based on these findings, this study selected 400 m as the grid cell size. At this scale, the research area was divided into 2420 grid cells, establishing the spatial foundation for subsequent LCZ classification and analysis.

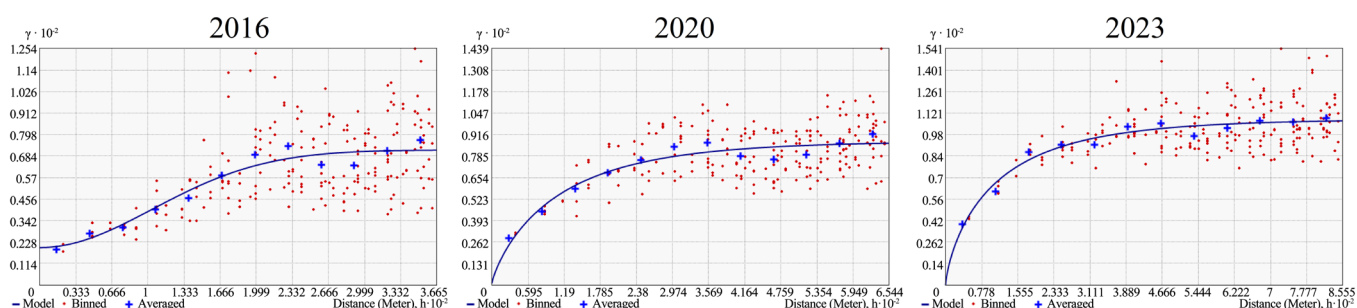


**Figure 2.** Semi-variogram model of building height from 2016 to 2023.

#### 3.1.2. Spatio-Temporal Pattern Analysis of Local Climate Zone Parameters

Figure 3 and Table 3 demonstrate that urbanization in Tongren City from 2016 to 2023 was the dominant driver of spatio-temporal changes in LCZ parameters. Regarding land cover, the proportion of PSF decreased from 93.75% to 90.52%, while ISF expanded

by 51.6%, indicating encroachment on natural/semi-natural surfaces in low-relief areas such as valleys and basins. Farmland was the most vulnerable land type during urban expansion, with its area decreasing by 9.4%. Forest area increased by 6.1% locally due to ecological interventions, whereas grassland irrigation systems declined by 15.4% owing to ecological fragility. Surface roughness exhibited significant spatial differentiation, with low-value areas dropping from 62% to 41% and medium-/high-value areas rising by 21%, forming a ‘roughness corridor’ that extended along major transport arteries with a peak increase of  $2.3\times$  in core zones. Although low-value areas near water systems contracted by 28%, ecological protection areas maintained zero growth, highlighting the rigid constraints of terrain and policy on mountainous urban forms.

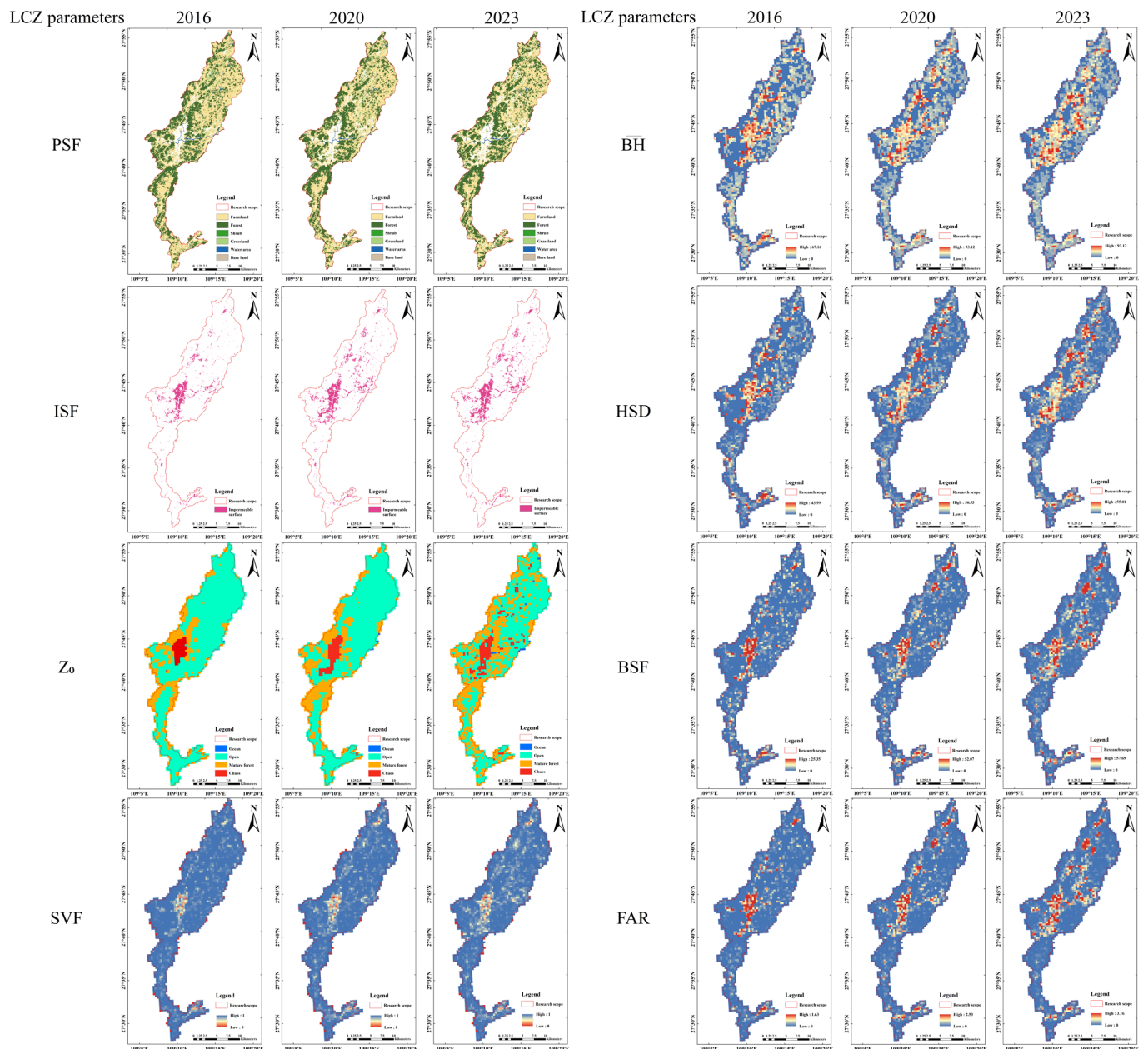


Figure 3. Spatio-temporal distribution of LCZ parameters from 2016 to 2023.

**Table 3.** Changes in land cover types in the study area from 2016 to 2023 (km<sup>2</sup>).

| Land Cover |            | 2016   |        | 2020   |        | 2023   |        |
|------------|------------|--------|--------|--------|--------|--------|--------|
| PSF        | Farmland   | 184.48 | 53.51% | 171.41 | 49.72% | 167.06 | 48.46% |
|            | Forest     | 129.13 | 37.46% | 132.58 | 38.46% | 137.05 | 39.75% |
|            | Shrub      | 0.60   | 0.17%  | 0.17   | 0.05%  | 0.09   | 0.03%  |
|            | Grassland  | 5.60   | 1.62%  | 7.29   | 2.11%  | 4.74   | 1.37%  |
|            | Water area | 3.38   | 0.98%  | 3.34   | 0.97%  | 3.09   | 0.90%  |
|            | Bare land  | 0.01   | 0.00%  | 0.04   | 0.01%  | 0.05   | 0.01%  |
|            | Overall    | 323.20 | 93.75% | 314.79 | 91.31% | 312.08 | 90.52% |
| ISF        |            | 21.55  | 6.25%  | 29.96  | 8.69%  | 32.67  | 9.48%  |

Architectural morphology exhibited distinct stratified differentiation during the observational period. The core area demonstrated accelerated vertical intensification from 2016 to 2020, evidenced by a 32% increase in buildings exceeding 50 m and a 37% expansion of high-density zones. This development coincided with significantly reduced sky visibility (areas with Sky View Factor (SVF) < 0.5 increased by 28%), achieving three-dimensional saturation. Post 2020 witnessed growth stagnation with strategic shifts toward existing stock renewal. Concurrently, edge areas displayed gradient diffusion along transportation corridors, where building parameter increments in transition zones remained substantially lower ( $p < 0.01$ ) than core measurements. Ecological zones maintained minimal fluctuations at 3% and 2% growth rates, respectively. New construction adopted radial dispersion patterns characterized by tentacle-like distributions, reflecting mountainous urban expansion's fundamental dependence on terrain gradients and transport infrastructure. Collectively, these dynamics followed the sequential mountain spatial logic: initial core polarization and densification, subsequent edge corridor penetration, and ultimate ecological resistance.

### 3.1.3. Identification of Local Climate Zone Types

Through localized research, the framework of the local climate zoning (LCZ) classification system in Tongren City was optimized, with modifications applied to specific parameters in the standard system [7] for targeted adjustments. As shown in Figure 4, the 15-category classification comprises five land cover types and ten building types. The building types include LCZ-1 (Compact high-rise), which is a densely distributed high-rise building. The building materials are mainly glass curtain walls and concrete, and the vegetation is scarce. LCZ-2 (Compact middle layer) is a middle-floor terraced building, mainly using a brick-concrete structure, with limited courtyard space. LCZ-3 (Compact low floor) is a dense collection of low and traditional residential buildings with small building spacing and mostly paved ground. LCZ-4 (Open senior level) is a high-rise building with a scattered layout, surrounded by green spaces and parking lots. LCZ-5 (Open middle level) is a combination of medium-height buildings and courtyards, with relatively rich vegetation coverage. LCZ-6 (Open lower level) is a sparsely distributed single-family low-rise residential complex with a high proportion of surrounding green space. LCZ-7 (Lightweight low-rise) is a shed or temporary building constructed with simple materials, and its roof is mostly made of metal or asphalt. LCZ-8 (Large low-rise) is a single-story large-scale building, commonly found in warehouses and shopping malls, with roofs made of metal or asphalt materials. LCZ-9 (Sparsely building) are independent buildings scattered on the natural surface, mainly surrounded by bare soil or vegetation. LCZ-10 (Industrial zone) is characterized by factories, chimneys, and hardened sites, with sparse vegetation and a large heat capacity. This classification effectively depicts the physical structure and thermal characteristics of the underlying surface of Tongren City. The types of land cover include LCZ-AB (Dense/sparse forest), LCZ-CD (Shrubs/low vegetation),

LCZ-E (Hard surface), LCZ-F (Bare soil sandy land), and LCZ-G (Water snowfield). This classification precisely characterizes the physical properties of urban underlying surfaces, providing a clear framework for analyzing their thermal environmental effects. This adjustment enhanced the system's applicability to Tongren's mountainous urban morphology.

### Built types

1. Compact high-rise
2. Compact middle layer
3. Compact low floor
4. Open senior level
5. Open middle level
6. Open the lower level
7. Lightweight low-rise
8. Large low-rise
9. Sparse building
10. Industrial zone

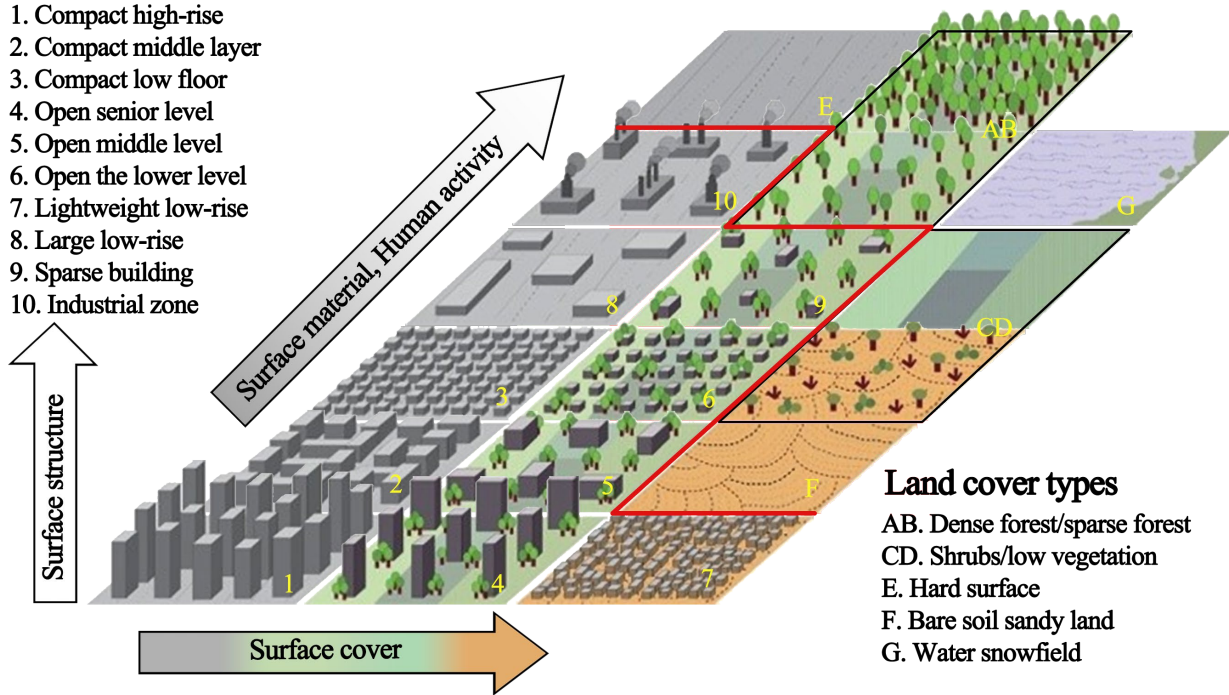


**Figure 4.** Schematic diagram of 15 LCZ types in Tongren City.

### 3.2. Analysis of Spatio-Temporal Variation in Local Climate Zones (LCZ) for Tongren City

#### 3.2.1. Analysis of Quantitative Changes in Local Climate Zone (LCZ) Parameters

As depicted in Figure 5 and Table 4, the evolution of LCZ in Tongren City from 2016 to 2023 exhibited land cover type dominance alongside diminished fluctuations and pronounced differentiation in building types. The land coverage ratio declined from 62.24% to 59.23% between 2016 and 2020, subsequently rising to 60.02% by 2023. Among building types, LCZ-1 surged by 2900%, with growth rates accelerating from 200% to 900% post 2020, whereas LCZ-8 decreased sharply by 61.11%, reflecting the replacement of low-rise construction by high-rise intensification in the core area. Surface cover transformations were drastic: LCZ-F and LCZ-G rose by 1300% and 1000%, respectively, while LCZ-CD fell by 47.58%. The heightened rate of change since 2020 signals disturbances to the fragile mountain ecosystem, attributable to economic stimuli and climate events.

**Table 4.** Mutual annual change rates of local climate zone types in 2016, 2020, and 2023 by annual overall change rate (%).

|           | LCZ-1 | LCZ-2 | LCZ-3 | LCZ-4  | LCZ-5 | LCZ-6  | LCZ-7 | LCZ-8  | LCZ-9 | LCZ-10 | LCZ-AB | LCZ-CD | LCZ-E  | LCZ-F | LCZ-G | Overall Change |                 |
|-----------|-------|-------|-------|--------|-------|--------|-------|--------|-------|--------|--------|--------|--------|-------|-------|----------------|-----------------|
|           |       |       |       |        |       |        |       |        |       |        |        |        |        |       |       | Building Type  | Land Cover Type |
| 2016–2020 | 200   | −9.09 | 64.21 | 8.33   | 35.48 | −2.92  | 150   | −14.29 | 150   | 83.33  | 17.40  | −13.13 | 350    | 400   | 100   | 37.76          | 62.24           |
| 2020–2023 | 900   | 175   | 8.97  | 130.77 | 33.33 | −20.27 | 80    | −61.11 | −20   | 3.03   | 122.11 | −47.58 | −66.67 | 180   | 450   | 40.77          | 59.23           |
| 2016–2023 | 2900  | 150   | 78.95 | 150    | 80.65 | −22.59 | 350   | −66.67 | 100   | 88.89  | 160.77 | −54.47 | 50     | 1300  | 1000  | 39.98          | 60.02           |

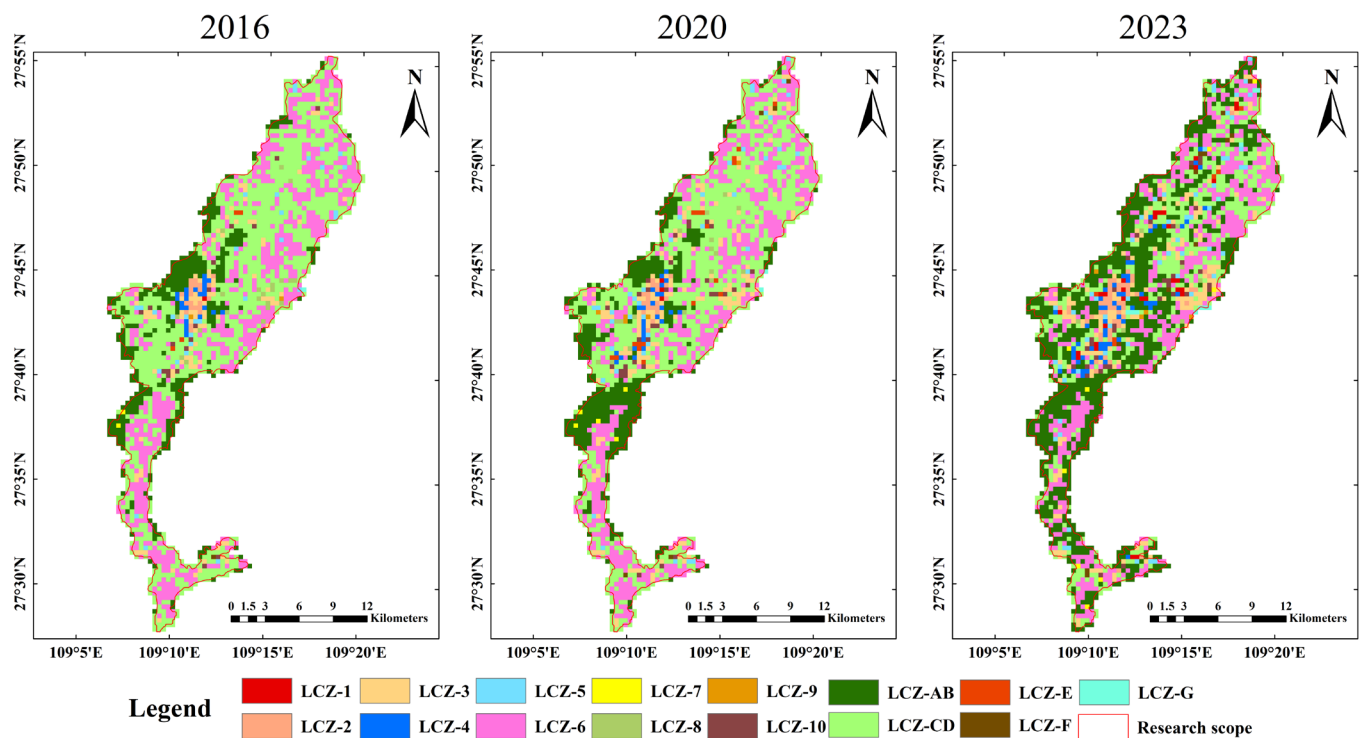


**Figure 5.** Local climate zoning maps of Tongren City in 2016, 2020, and 2023.

As shown in Appendix A, the transitional evolution of LCZ types in Tongren City from 2016 to 2020 and 2023 resulted in significant land cover changes. The forest area increased by 8688 hectares, primarily due to the 72% conversion from shrubs and grasslands. Concurrently, LCZ-3 in compact built-up areas expanded by 1200 hectares, while LCZ-CD, characterized by grass-irrigated areas and serving as the largest transfer-out source, declined sharply by 9968 hectares. Regarding ecological vulnerability, low-rise areas designated as LCZ-6 decreased by 2480 hectares, with some zones being upgraded to compact areas or reverting to forest. Post 2020, the transformation process accelerated, leading to intensification in the core area from low-density (LCZ-6) to compact (LCZ-3) development. In contrast, the marginal shrub and grass belt (LCZ-CD) experienced simultaneous urban encroachment and ecological replacement. The spatial differentiation is further emphasized by an 85.8% retention rate of LCZ-AB in stable cores and a 39.2% retention rate of LCZ-CD in upheaval zones, highlighting the varied responses of mountain systems to human interventions.

To evaluate the reliability of the classification results, the accuracy of the results was verified. The accuracy was evaluated by randomly generating verification points. We randomly generated several sample points, manually interpreted them by comparing with high-definition images (Google Earth), generated the confusion matrix and calculated the overall accuracy and Kappa coefficient. As shown in Appendix B, the Kappa coefficients of the LCZ classification results obtained through the confusion matrix in this study reached 0.93, 0.93, and 0.95, respectively, demonstrating extremely high and stable accuracy, all belonging to a high consistency level, which fully proves the effectiveness and robustness of this method.

### 3.2.2. Spatial Pattern Evolution of Local Climate Zone (LCZ) Distributions

As illustrated in Figure 5, the spatial distribution of local climate zones (LCZ) in Tongren City exhibits a characteristic differentiation pattern. Within this pattern, the core high-rise area (LCZ-1/LCZ-4) extends along primary transportation corridors while

progressively engulfing low-density residential zones (LCZ-6). Concurrently, the peripheral industrial belt (contiguously LCZ-10/LCZ-7) compresses natural landscapes, contributing to the development of a continuous heat island gradient driven by high-level patches in the central area. The northwestern mountainous region retains stable forest cores (LCZ-AB) due to topographic constraints, whereas the southern shrub and grassland belt (LCZ-CD) has been fragmented into ecological islands. Newly developed mid-rise areas (LCZ-5) cluster along riverways, forming water-adjacent residential districts, while industrial zones actively avoid riparian corridors. Notably, edge bare land (LCZ-F) and lightweight construction (LCZ-7) replace impervious surfaces (LCZ-E), and the former industrial storage zone (LCZ-8) evolves into a mosaic texture where high-rise residences intersect with legacy structures.

As illustrated in Figure 6, four representative sample transects were selected to analyze the spatial evolution of local climate zones (LCZ) types. The A-A transect traverses east–west along the main river, capturing river-aligned urban development. The B-B transect extends north–south from the Xiaojiang River to Xieqiao, reflecting terrain-constrained development patterns. The C-C transect crosses east–west between Chuandong and Liangwan, representing fringe expansion dynamics. Finally, the D-D transect follows a north–south orientation from Daxing to Dengta, demonstrating transportation corridor-driven urbanization.

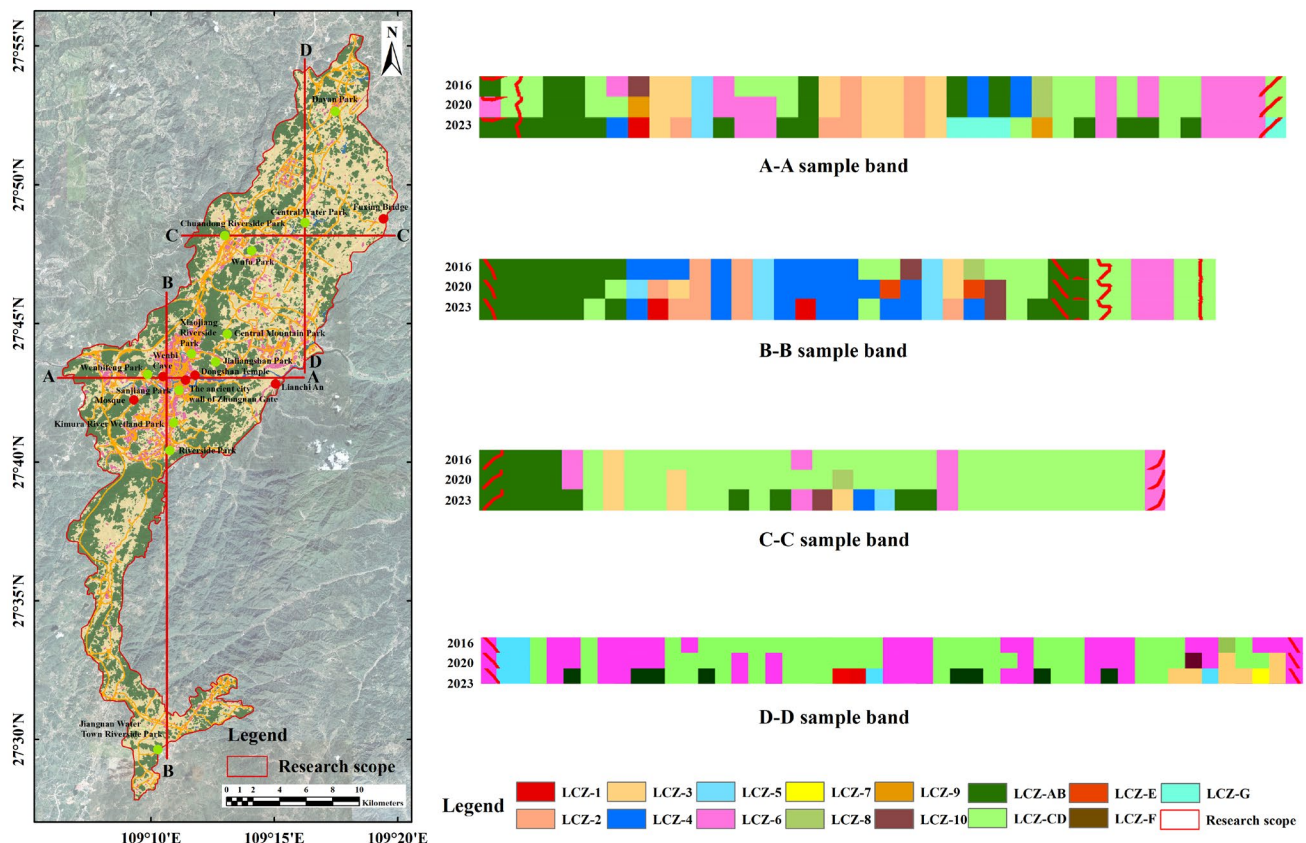


**Figure 6.** Spatial variations of local climate zone types in Tongren City from 2016 to 2023.

Sample transect analysis reveals distinct spatial evolution patterns in Tongren City's local climate zones (LCZ). Along the riverbank zone (A-A), residential areas (LCZ-5/LCZ-6) have completely replaced vegetated areas (LCZ-CD), while the eastern industrial belt (LCZ-10) expanded by 300% along the river, forming a consolidated production shoreline. In the valley belt (B-B), northern slope forests (LCZ-AB) remain preserved due to topographic constraints, whereas the southern valley has been densely transformed into mixed residential and storage zones. The urban fringe (C-C) exhibits gradient encroachment, with

western high-rise enclaves (LCZ-9) entirely replaced by shrubland, and eastern suburban light industrial zones (LCZ-7/LCZ-10) occupying 89% of the original vegetation reserve. Within the traffic radiation corridor (D-D), 75% of the road axis is now covered by high-rise developments (LCZ-1/LCZ-4), fragmenting peripheral forests (LCZ-AB) into isolated islands interspersed with open residential areas (LCZ-5). This configuration demonstrates a mountainous spatial paradigm prioritizing waterfront construction, compromising valley development, and polarizing road network guidance.

### 3.3. Spatio-Temporal Evolution Analysis of Surface Temperature Dynamics

Figure 7 illustrates the spatio-temporal evolution of the urban heat island (UHI) effect in Tongren City's core area, transitioning from a patchy single-core pattern in 2016 to multi-core aggregation by 2022, and subsequently fragmenting in 2023. The persistent summer high temperatures reflect pronounced urban heat storage effects. Winter cold islands in western mountainous areas maintained 30% coverage stability through 2022 but expanded by 27.8% in 2023, forming distinct cold-air intrusion corridors that permeate urban fringes. Autumn exhibits a fragmented equilibrium dominated by mesothermal transition zones, indicating a dual-process thermal regime characterized by constrained core warming and amplified peripheral cooling.

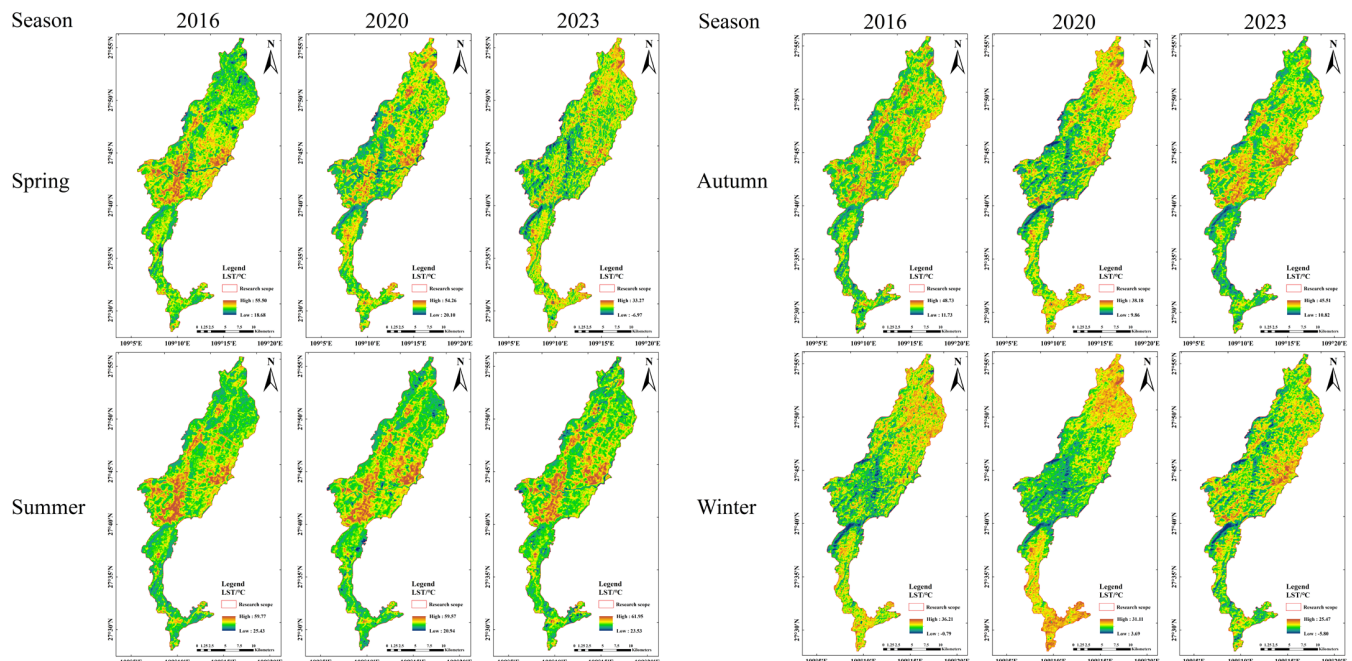


**Figure 7.** Spatio-temporal distribution of surface temperature in Tongren City in 2016, 2022, and 2023.

Table 5 reveals pronounced seasonal polarization in Tongren City's surface thermal regime, with summer exhibiting persistently high urban heat island (UHI) coverage (30%) alongside continuous expansion of extreme high-temperature zones. Conversely, winter maintains approximately 30% cold island coverage but demonstrates a 125% annual intensification of low-temperature intensity. Spring shows an initial 48.3% UHI increase followed by abrupt decline due to climatic anomalies, while autumn features a 25.4% expansion of mesothermal transition zones that buffer heat-cold contrasts. This spatio-temporal pattern reflects three distinct mechanisms: summer heat storage release on impervious surfaces (LCZ-1/LCZ-3), winter cold source maintenance in northwestern forests (LCZ-AB), and spring-autumn thermal instability triggered by climatic variability.

**Table 5.** Proportion (%) of the 7 LST levels in Tongren City from 2016 to 2023.

| LST Partition           |                            | Scope<br>(°C) | 2016   |        |        |        | 2020   |        |        |        | 2023   |        |        |        |        |
|-------------------------|----------------------------|---------------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
|                         |                            |               | Spring | Summer | Autumn | Winter | Spring | Summer | Autumn | Winter | Spring | Summer | Autumn | Winter | Spring |
| Heat island             | Extremely high temperature | ≥45           | 0.014  | 0.033  | 0.002  | 0.000  | 0.016  | 0.463  | 0.000  | 0.000  | 0.000  | 0.239  | 0.000  | 0.000  | ≥45    |
|                         | High temperature           | 36–44         | 0.081  | 3.547  | 0.034  | 0.000  | 1.542  | 13.568 | 0.002  | 0.000  | 0.000  | 11.020 | 0.039  | 0.000  | 36–44  |
|                         | Relative high temperature  | 28–35         | 19.342 | 26.282 | 12.882 | 0.011  | 27.292 | 15.975 | 0.077  | 0.001  | 0.026  | 18.691 | 4.678  | 0.000  | 28–35  |
|                         | In total                   |               | 19.437 | 29.863 | 12.918 | 0.011  | 28.851 | 30.006 | 0.078  | 0.001  | 0.026  | 29.949 | 4.717  | 0.000  | 19.437 |
| Medium-temperature zone | Medium-temperature zone    | 19–27         | 10.692 | 0.267  | 17.398 | 1.190  | 1.279  | 0.124  | 24.463 | 0.816  | 16.728 | 0.181  | 25.392 | 0.017  | 10.692 |
|                         | Relative low temperature   | 11–18         | 0.001  | 0.000  | 0.014  | 28.640 | 0.000  | 0.000  | 5.588  | 27.170 | 13.568 | 0.000  | 0.021  | 2.261  | 0.001  |
|                         | Low temperature            | 1–10          | 0.000  | 0.000  | 0.000  | 0.488  | 0.000  | 0.000  | 0.001  | 2.143  | 0.006  | 0.000  | 0.000  | 27.849 | 0.000  |
|                         | Extremely low temperature  | ≤0            | 0.000  | 0.000  | 0.000  | 0.001  | 0.000  | 0.000  | 0.000  | 0.000  | 0.001  | 0.000  | 0.000  | 0.003  | 0.000  |
|                         | In total                   |               | 0.001  | 0.000  | 0.014  | 29.128 | 0.000  | 0.000  | 5.589  | 29.313 | 13.576 | 0.000  | 0.021  | 30.113 | 0.001  |
| Cold Island             |                            |               |        |        |        |        |        |        |        |        |        |        |        |        |        |

To evaluate the reliability of the inversion results, the accuracy of the results obtained from data inversion was verified. For the Landsat 8–9 data, in this study, the surface temperature band (ST\_B10) provided in the USGS Landsat Collection 2 Level 2 product was directly adopted as the inversion result. This product is generated by USGS based on the official algorithm and has reliable accuracy guarantee. For the Landsat 7 C2L1 data, cross-validation was conducted with the Landsat 7 Collection 2 Level 2 surface temperature product (ST\_B6 band) officially released by USGS at the same time. As shown in Figure 8, through sampling verification of the results from multiple periods, the coefficient of determination ( $R^2$ ) reached 0.93, 0.88, and 0.75, respectively. This result indicates that the inversion method adopted in this study exhibits excellent performance at different times. The results are highly consistent with authoritative products, with reliable accuracy, and can be used for subsequent spatio-temporal variation analysis.

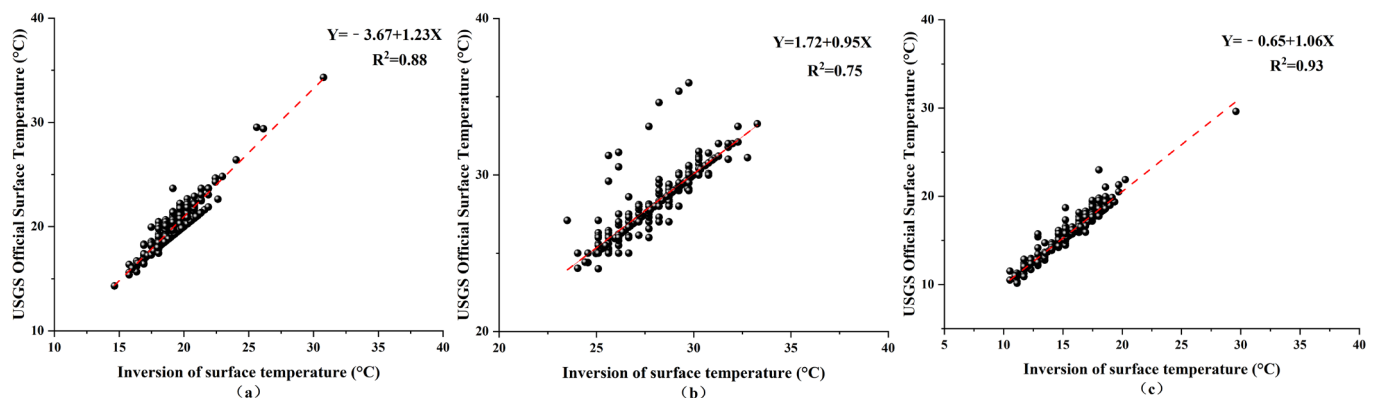


**Figure 8.** Verification of surface temperature inversion results based on Landsat data. Among them, (a) the verification of Landsat7 in the spring of 2023; (b) the verification of Landsat7 in the fall of 2016; (c) the verification of Landsat7 in winter 2016.

### 3.4. Correlation Analysis Between LCZ Types and Heat Island Intensity Gradients

Surface urban heat island intensity (SUHII) was selected as the analytical indicator due to significant interannual surface temperature variations in Tongren City. As demonstrated in Figure 9 and Table 6, thermal differentiation across local climate zones (LCZ) reveals a distinct pattern characterized by industrial high-heat polarization, pronounced cold signatures in water bodies and forests, and building density-mediated temperature control. The industrial zone (LCZ-10) exhibited peak summer heat island intensity of 6.05 °C in 2020, exceeding compact high-rise areas (LCZ-1) by 12%, with this temperature differential progressively expanding—indicating escalating industrial heat dissipation risks. Water bodies (LCZ-G) displayed seasonal cold island reversal, registering winter temperatures of −1.44 °C while achieving summer cooling to −5.40 °C (2023), with cooling efficiency surpassing forested zones (LCZ-AB).

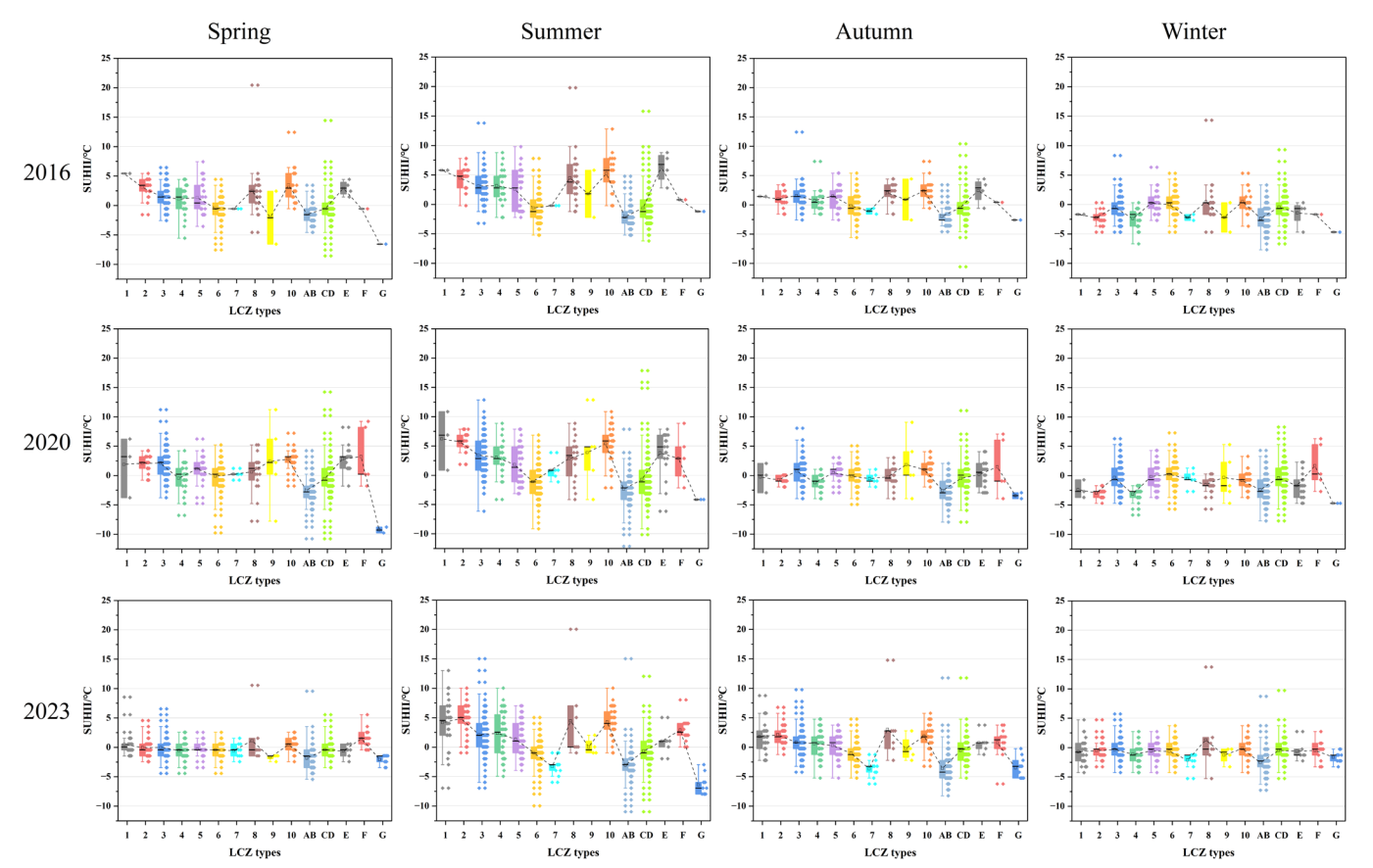


Figure 9. Variation of heat island intensity in Tongren City from 2016 to 2023 in four seasons.

Table 6. Changes in average heat island intensity of local climate zone types from 2016 to 2023 (°C).

| Season | Year     | LCZ Types |       |       |       |       |       |       |       |       |       |       |       |       |       |       |
|--------|----------|-----------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
|        |          | 1         | 2     | 3     | 4     | 5     | 6     | 7     | 8     | 9     | 10    | AB    | CD    | E     | F     | G     |
| Spring | 2016     | 5.72      | 3.65  | 2.16  | 1.62  | 1.76  | 0.02  | 0.28  | 2.99  | -1.14 | 3.99  | -0.87 | 0.00  | 3.15  | -0.03 | 0.16  |
|        | 2020     | 3.19      | 2.73  | 2.56  | 0.04  | 1.74  | 0.31  | 0.49  | 1.37  | 2.92  | 3.44  | -1.92 | 0.00  | 2.87  | 3.89  | 0.18  |
|        | 2023     | 0.88      | 0.55  | 0.51  | -0.22 | 0.33  | 0.01  | -0.29 | 1.05  | -1.31 | 0.91  | -1.41 | 0.00  | 0.00  | 2.12  | -1.48 |
|        | In total | -4.84     | -3.10 | -1.65 | -1.85 | -1.43 | -0.01 | -0.58 | -1.95 | -0.17 | -3.08 | -0.54 | -0.01 | -3.16 | 2.15  | -1.64 |
| Summer | 2016     | 6.40      | 4.90  | 3.64  | 3.55  | 2.99  | -0.13 | 0.22  | 4.78  | 2.29  | 5.82  | -1.41 | 0.00  | 6.38  | 0.82  | 0.21  |
|        | 2020     | 7.30      | 6.12  | 3.90  | 3.50  | 2.35  | -0.57 | 0.78  | 3.69  | 4.39  | 6.05  | -1.66 | 0.00  | 4.57  | 3.38  | 0.22  |
|        | 2023     | 4.38      | 5.52  | 2.73  | 2.86  | 1.99  | -0.53 | -2.53 | 4.55  | -0.37 | 4.88  | -2.50 | 0.00  | 1.99  | 2.74  | -5.40 |
|        | In total | -2.02     | 0.62  | -0.91 | -0.69 | -1.00 | -0.39 | -2.73 | -0.23 | -2.66 | -0.94 | -1.08 | 0.00  | -4.39 | 1.92  | -5.61 |
| Autumn | 2016     | 1.57      | 1.49  | 2.10  | 1.05  | 1.96  | 0.29  | 0.37  | 2.38  | 1.59  | 3.04  | -1.50 | 0.00  | 2.65  | 0.63  | 0.12  |
|        | 2020     | 1.05      | -0.26 | 1.28  | -0.93 | 1.11  | 0.28  | -0.14 | 0.65  | 2.32  | 1.54  | -2.03 | 0.00  | 0.34  | 2.00  | -0.06 |
|        | 2023     | 2.11      | 2.71  | 1.45  | 0.96  | 0.83  | -0.58 | -3.08 | 3.54  | -0.39 | 2.49  | -2.97 | 0.00  | 1.45  | 1.39  | -3.34 |
|        | In total | 0.54      | 1.22  | -0.65 | -0.09 | -1.14 | -0.87 | -3.45 | 1.16  | -1.98 | -0.55 | -1.46 | 0.00  | -1.21 | 0.76  | -3.46 |
| Winter | 2016     | -0.48     | -1.93 | -0.08 | -1.95 | 0.62  | 0.41  | -1.62 | 1.04  | -1.36 | 1.22  | -1.94 | 0.00  | -1.21 | -1.63 | -0.12 |
|        | 2020     | -1.35     | -2.34 | 0.23  | -2.82 | 0.37  | 0.65  | 0.06  | -1.00 | 0.12  | -0.35 | -1.92 | 0.00  | -1.69 | 2.36  | -0.13 |
|        | 2023     | -0.54     | 0.00  | 0.20  | -0.73 | -0.04 | -0.19 | -1.61 | 1.72  | -1.17 | 0.46  | -1.99 | 0.00  | 0.01  | 0.14  | -1.44 |
|        | In total | -0.09     | 1.93  | 0.28  | 1.21  | -0.65 | -0.60 | 0.00  | 0.67  | 0.18  | -0.77 | -0.05 | 0.00  | 1.22  | 1.77  | -1.32 |

SUHII in compact built-up areas (LCZ-1–LCZ-3) remained consistently elevated (>2.16 °C), whereas open areas (LCZ-4–LCZ-5) showed minimal fluctuations. Notably, extensive low-rise development (LCZ-8) exhibited anomalous heating (32% above LCZ-3) due to equipment emissions, while light industrial zones (LCZ-7, 70% coverage) uniquely maintained cold island conditions year-round. During 2020, industrial heat islands (LCZ-10) and winter heat anomalies on bare land (LCZ-F) increased by 178% annually through synergistic interaction. Compact high-rises (LCZ-1) experienced 83% spring heat island intensification following climatic anomalies. By 2023, vegetation cold islands reached historic extremes (LCZ-AB/CD summer: −2.50 °C), evidencing enhanced thermal buffering from ecological restoration. These dynamics collectively demonstrate mountainous urban thermal regimes defined by:

1. Rigid heat radiation in high-density built environments.
2. Uncontrolled industrial geothermal release.

### 3. Resilient temperature regulation in blue–green spaces.

#### 3.5. Significance of Local Climate Zone (LCZ) Parameters for Seasonal Heat Island Intensity Variations

Figure 10 reveals a transformational trend in the driving mechanisms of Tongren City's surface urban heat island intensity (SUHII) from 2016 to 2023, characterized by a shift from two-dimensional surface hardening dominance to three-dimensional spatial form regulation. In 2016, surface coverage parameters prevailed, with impervious surface fraction (ISF) contributing 30–40% at its peak—highlighting surface hardening as the primary urbanization-driven heat island driver. Building surface fraction (BSF) and floor area ratio (FAR) followed at 20–25%, reflecting volumetric expansion synergies in newly developed areas. By 2020, architectural form indicators gained prominence as BSF/FAR and ISF became co-dominant drivers, emphasizing the thermal influence of three-dimensional urban structures. The most significant transformation occurred in 2023 when sky view factor (SVF) and building height (planar surface fraction, PSF) contributions surged to 20–25%, surpassing ISF as the dominant forcing mechanism. Concurrently, pervious surface fraction (PSF) demonstrated enhanced mitigation effects, signaling an urban planning transition from suppressing land hardening to optimizing three-dimensional ventilation efficiency.

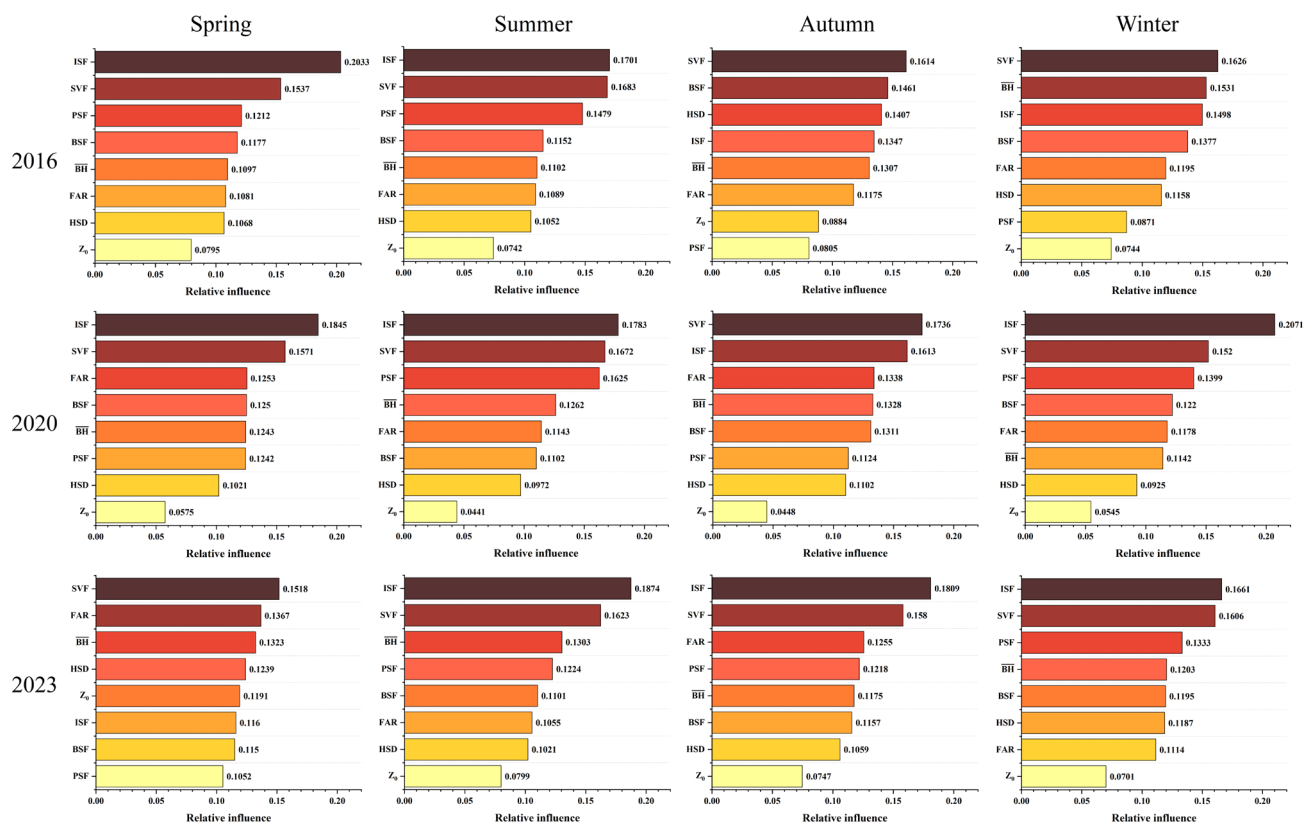


**Figure 10.** Relative influence of heat island intensity of local climate zone parameters in Tongren City in 2016, 2022, and 2023.

During summer, impervious surface fraction (ISF) remained dominant (30–40% peak contribution), while sky view factor (SVF) regulatory efficiency significantly improved (25% in 2023), indicating that shading designs alleviated extreme temperatures. Winter patterns showed terrain roughness ( $Z_0$ ) and building height ( $BH$ ) as co-dominant drivers (20–25% contribution), highlighting dual modulation of mountain inversion layers through geomorphology and vertical structures. Transitional seasons were governed by building density (BSF/FAR, 22–28%), revealing persistent thermal inertia effects. Long-term

trends indicated ISF, BSF, and FAR continuously exacerbated heat islands (10–15% average annual contribution increase), whereas SVF,  $\overline{BH}$ , and pervious surface fraction (PSF) enhanced cooling (10–20% annual gain). Enhanced PSF effectiveness during 2023 autumn defoliation (20–25%) and SVF breakthroughs in winter ventilation (22%) validated ecological-intelligent interventions.

## 4. Discussion

### 4.1. Relationship Between Local Climate Zoning and Urban Heat Island Intensity in Tongren City

Liu Y et al. [21,51,52] studied the relationship between local climate zones (LCZ) and heat island intensity in plain cities like Guangzhou. They found that the heat island effect was the strongest in compact low-rise and heavy industrial areas, while the heat island intensity in open high-rise and open mid-rise areas was significantly higher than that in low-rise types. Spatial distribution gradients of the same LCZ types exist, with heat island intensity generally higher in central urban areas compared to peripheral regions. Among them, Tian Liu's research focused on Chongqing, a typical mountainous city, systematically analyzing the spatio-temporal characteristics of its thermal environment and the universal influence mechanism of LCZ. This study further supplements and deepens its findings, pointing out that in specific mountainous terrains, the standard LCZ classification needs to incorporate terrain factors for correction, and its thermal behavior may significantly deviate from the general pattern. It emphasized the decisive role of terrain in shaping the urban thermal environment. This study corroborates these findings. However, our investigation revealed that 80% of large low-level LCZ areas in Tongren function as high-temperature isolated islands, whereas light industrial LCZ-7 zones instead become cold islands. Additionally, industrial areas and bare land LCZ-F form a thermal synergy zone. The underlying reasons for these observations include the location of industrial areas in mountain cities like Tongren within river valleys, which restricts ventilation and impedes heat dissipation. High transportation costs in mountainous regions compel localized high-energy-consuming production, intensifying heat release. Steep slopes necessitate dense arrangements of large heat dissipation devices in low-rise buildings. Clean mountain air flows penetrate open light industrial plants (LCZ-7), establishing local ventilation corridors. Furthermore, bare rock on steep slopes (LCZ-F) is more susceptible to heat accumulation due to solar radiation angle effects. Moreover, due to the adjustments made to the standard LCZ classification method in practice in this study to adapt to high altitude differences and complex slope orientations, more topographic factors were considered in the classification process rather than just buildings and materials. The understanding of the applicability of LCZ in mountainous urban environments has been enhanced, highlighting the unique thermal behavior of the industrial and bare land areas in Tongren City. By identifying local factors, such as ventilation limitations induced by valleys and sunlight exposure driven by slopes, our research results provide a comprehensive framework for LCZ classification adapted to complex terrains, thereby supporting more targeted urban thermal management strategies in similar geographical contexts.

### 4.2. Influence of Local Climate Zone Parameters on Seasonal Surface Urban Heat Island Intensity in Tongren City

In studies examining the influence of local climate zone (LCZ) parameters on seasonal heat island intensity, Yang et al. [53–56] identified summer-built environments (LCZ 7/8) as exhibiting the most pronounced heat island effects. Their findings highlighted building surface fraction (BSF) and impervious surface fraction (ISF) as primary drivers, while water bodies and green spaces demonstrated significant cooling effects. Winter analyses further revealed the sky view factor (SVF) as a critical modulator of thermal conditions.

While this study corroborates these observations, our 2023 data from Tongren revealed a notable shift: SVF and building height superseded ISF as dominant drivers of thermal dynamics. This transition reflects the terrain roughness and vertical development constraints typical of mountainous cities, where scarce land resources compel upward urban expansion. Consequently, building height and SVF have replaced horizontal sprawl as pivotal thermal regulators. Mechanistically, the valley wind corridor effect in Tongren enhances local ventilation efficiency through SVF optimization. Simultaneously, building height mediates solar radiation reception across slopes, with steeply sloped structures exhibiting instantaneous alterations in shadow coverage—a key modifier of microclimatic variability. Our research contributes to the field by elucidating the shifting significance of LCZ parameters in mountainous cities, underscoring the dominance of SVF and building height over traditional factors like ISF. This insight refines the theoretical foundation of thermal regulation mechanisms in vertically constrained environments and offers practical guidance for incorporating terrain-specific metrics into urban climate modeling and design practices.

#### *4.3. Urban Planning Strategies for Climate Adaptation in Tongren City*

To mitigate urban heat island effects in Tongren City, this study proposes a comprehensive planning strategy integrating spatial structure optimization, ecological function enhancement, and climate adaptation mechanisms. This approach converts three-dimensional spatial transformations into planning dividends, specifically addressing three critical conflicts: industrial thermal polarization, the fragmentation of blue–green networks, and mountainous terrain constraints. Firstly, industrial heat source management requires relocating high-energy-consumption industries (LCZ-10) from heat-retention valleys to well-ventilated slopes while concurrently covering existing industrial zones with composite cooling systems to suppress uncontrolled heat dissipation. Secondly, blue–green space enhancement involves restoring natural river morphology to amplify the cooling efficiency of aquatic LCZ-G summer cold islands; embedding artificial wet ponds in industrial–residential transition zones to establish distributed cold sources; and planting nitrogen-fixing shrubs in ecologically deficient LCZ-CD shrub–grass belt dead zones to restore hydrothermal regulation resilience. Finally, a two-tiered ventilation system will be constructed along prevailing wind directions and river corridors; primary corridors maintain 200 m-wide riparian buffers connecting cold cores. Collectively, these strategies achieve heat island mitigation while maintaining dynamic equilibrium between urban development and ecological security, providing critical support for climate-adaptive urban planning [57]. The planning strategies proposed herein provide a tailored approach for mitigating thermal challenges in mountainous cities, directly addressing Tongren’s unique geographic and industrial context. By integrating ecological restoration with ventilative design and industrial repositioning, this study offers a transferable model for promoting climate resilience in similar topographically complex regions, thereby bridging the gap between theoretical research and actionable urban planning interventions.

## **5. Conclusions**

This study focuses on Tongren City, a typical high-temperature mountainous area in China characterized by pressing needs for climate-adaptive urban planning. Employing the local climate zone (LCZ) framework and multi-temporal remote sensing data, this research systematically investigates the spatio-temporal coupling characteristics between surface urban heat island intensity (SUHII) and LCZ types through integrated LCZ classification mapping combined with land surface temperature inversion. The main innovation of this

study lies in the first systematic application and verification of the seasonal adaptability and spatial explanatory power of the LCZ framework in high-temperature mountainous cities in China. It has clarified that the contribution of three-dimensional morphological factors to the regulation of the heat island exceeds that of traditional two-dimensional indicators, and it has proposed the evolution path of “ecological deficits-heat island synergy” and the seasonal heat mitigation framework. It provides quantitative basis and theoretical innovation for mountain city planning. The main research results are summarized as follows: (1) The evolution of LCZ types in Tongren City shows an ecological deficit with a net increase in the low-cover area of the woodland type (LCZ-AB) and a net decrease in the shrub type area (LCZ-CD). (2) The high-rise built-up area (LCZ-1/4) expands along the main traffic arteries and replaces the low-rise and low-density residential areas (LCZ-6). The encroachment of industrial belts has led to ecological isolation and landscape fragmentation. (3) The thermal environment in Tongren shows the characteristic of “seasonal locking” between summer and winter. Spatially, the form of urban heat islands has evolved from a single-centered structure to a multi-centered one, and eventually to a fragmented pattern. (4) The driving mechanism of the heat island in Tongren City has gradually evolved from being dominated by impermeable surfaces to a three-dimensional form coordinated regulation. In winter, it is mainly driven by terrain roughness and building height; in summer, it is driven by the proportion of impermeable surfaces; and in spring and autumn, it is driven by building density. Through the above research results, in terms of supporting sustainable development, it serves as a warning that urban expansion should focus on ecological balance. It provides a reference for optimizing the spatial layout of towns and cities and avoiding the occupation of natural space. It provides a theoretical basis for climate-adaptive urban planning, which is conducive to promoting the construction of low-carbon and resilient cities and facilitating the coordinated development of society, economy and environment.

Therefore, this study makes a significant contribution to the field of sustainable development by providing a scientifically grounded framework for climate-adaptive urban planning. Our findings directly support the United Nations Sustainable Development Goals (SDGs), particularly SDG 11 (Sustainable Cities and Communities) and SDG 13 (Climate Action), by offering practical tools to mitigate urban heat islands—a critical challenge exacerbated by climate change. The quantitative insights into the spatio-temporal evolution of LCZs and SUHII equip urban planners and policymakers with the ability to define, measure, and monitor sustainability metrics related to the urban thermal environment. This research underscores that sustainable urban expansion in mountainous regions must prioritize the preservation of ecological buffers (e.g., LCZ-CD shrublands) and avoid landscape fragmentation to maintain ecosystem services and enhance urban resilience.

Furthermore, the proposed seasonal heat mitigation framework and the identification of key three-dimensional morphological drivers (e.g., building height, density, and terrain roughness) translate into actionable applications for sustainability. This enables the development of targeted policies and planning regulations that promote low-carbon, resilient urban forms. By optimizing spatial layout to reduce heat island effects, cities can lower energy consumption for cooling, improve public health, and protect biodiversity, thereby fostering a synergistic development path that balances socio-economic needs with environmental conservation. The methodology, verified in a typical high-temperature mountainous city, provides a replicable sustainability tool for underdeveloped mountainous cities globally, ensuring that urban growth is aligned with the principles of long-term sustainability.

There are several limitations in this study that need to be pointed out. Firstly, the LCZ classification system is based on international experience. The applicability of its classification standards and parameter thresholds in mountainous cities in China still needs further verification, and especially when dealing with complex terrains and mixed land use types, there may be recognition deviations. Secondly, the thermal infrared remote sensing data used in the research is limited by the spatial resolution of the sensors and the transit time, making it difficult to capture small-scale thermal environment variations and full-day dynamic characteristics, especially with limited analytical accuracy for the nighttime heat island effect. Furthermore, the model has not fully taken into account the unique wind–thermal environment interaction in mountainous cities, and it lacks the comprehensive integration of multi-dimensional factors such as local circulation, anthropogenic heat emissions, and indoor and outdoor heat exchange, which may affect the comprehensiveness of the analysis of the heat-island-driving mechanism.

Based on the current research achievements and deficiencies, future research will be carried out in the following directions: First, future research will integrate multi-source high-resolution remote sensing data with unmanned aerial vehicle (UAV) thermal imaging technology to enhance the accuracy and spatio-temporal continuity of LCZ classification and temperature inversion. Second, future research will construct a multi-dimensional driving factor subset that includes elements such as wind speed and direction, solar radiation, and anthropogenic heat, and it will develop a thermal environment mechanism model suitable for mountainous cities. Third, future research will enhance the practical connection between the LCZ framework and China’s urban planning system, and it will explore the path of incorporating the results of thermal environment assessment into the guidelines for territorial space planning and urban design. Fourth, future research will expand research in the social and humanistic dimensions, assess the implementation costs and benefits of heat mitigation strategies, and promote the transformation of climate adaptation planning from theoretical research to engineering application.

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## Appendix A

### Appendix A.1

**Table A1.** Development and changes of local climate zone types in Tongren City from 2016 to 2020 (ha).

| LCZ Types |    | 2020 |     |      |     |     |        |    |     |    |     |      |        |     |    |    | OA (2016) |
|-----------|----|------|-----|------|-----|-----|--------|----|-----|----|-----|------|--------|-----|----|----|-----------|
|           |    | 1    | 2   | 3    | 4   | 5   | 6      | 7  | 8   | 9  | 10  | AB   | CD     | E   | F  | G  |           |
| 2016      | 1  | 16   |     |      |     |     |        |    |     |    |     |      |        |     |    |    | 16        |
|           | 2  |      | 272 | 32   |     |     |        |    |     |    | 48  |      |        |     |    |    | 352       |
|           | 3  |      | 16  | 1360 | 32  | 16  |        |    |     |    | 32  |      | 64     |     |    |    | 1520      |
|           | 4  | 32   | 16  | 16   | 256 | 48  |        |    |     |    |     |      | 16     |     |    |    | 384       |
|           | 5  |      | 16  | 144  |     | 320 |        |    |     |    | 16  |      |        |     |    |    | 496       |
|           | 6  |      |     | 320  |     | 128 | 8960   | 32 | 16  |    | 32  | 704  | 768    | 16  |    |    | 10,976    |
|           | 7  |      |     |      |     |     |        | 32 |     |    |     |      |        |     |    |    | 32        |
|           | 8  |      |     | 144  |     |     |        |    | 64  |    |     |      | 96     | 32  |    |    | 336       |
|           | 9  |      |     | 16   |     |     |        |    |     | 16 |     |      |        |     |    |    | 32        |
|           | 10 |      |     | 16   | 16  |     |        |    |     | 16 | 192 |      | 16     | 16  | 16 |    | 288       |
|           | AB |      |     | 16   |     |     | 96     |    |     | 32 |     | 4576 | 704    |     |    |    | 5424      |
|           | CD |      |     | 432  | 112 | 160 | 1600   | 16 | 192 | 16 | 192 | 1088 | 14,208 | 192 | 48 | 16 | 18,272    |
|           | E  |      |     |      |     |     |        |    | 16  |    | 16  |      |        | 32  |    |    | 64        |
|           | F  |      |     |      |     |     |        |    |     |    |     |      |        |     | 16 |    | 16        |
|           | G  |      |     |      |     |     |        |    |     |    |     |      |        |     |    | 16 | 16        |
| OA (2020) |    | 48   | 320 | 2496 | 416 | 672 | 10,656 | 80 | 288 | 80 | 528 | 6368 | 15,872 | 288 | 80 | 32 | 38,224    |

**Table A2.** Development and changes of local climate zone types in Tongren City from 2020 to 2023 (ha).

| LCZ Types |    | 2023 |     |      |     |     |      |     |     |    |     |        |      |    |     |     | OA (2020) |
|-----------|----|------|-----|------|-----|-----|------|-----|-----|----|-----|--------|------|----|-----|-----|-----------|
|           |    | 1    | 2   | 3    | 4   | 5   | 6    | 7   | 8   | 9  | 10  | AB     | CD   | E  | F   | G   |           |
| 2020      | 1  | 48   |     |      |     |     |      |     |     |    |     |        |      |    |     |     | 48        |
|           | 2  | 16   | 256 |      | 32  | 16  |      |     |     |    |     |        |      |    |     |     | 320       |
|           | 3  |      | 288 | 1968 | 80  | 16  |      |     |     |    | 80  |        | 16   | 32 | 16  |     | 2496      |
|           | 4  | 48   | 48  |      | 240 |     |      |     |     |    | 32  |        | 32   |    |     | 16  | 416       |
|           | 5  |      | 64  | 64   | 464 |     |      |     |     |    | 16  |        |      |    |     |     | 672       |
|           | 6  |      |     | 144  | 16  | 128 | 7488 | 96  | 16  | 32 |     | 2432   | 208  |    | 32  | 32  | 10,656    |
|           | 7  |      |     |      |     | 16  | 48   | 16  |     |    |     |        |      |    |     |     | 80        |
|           | 8  | 16   | 16  | 128  | 16  |     | 16   |     | 48  | 16 |     |        | 32   |    |     |     | 288       |
|           | 9  | 16   | 16  | 16   |     |     | 16   |     |     |    | 16  |        |      |    |     |     | 80        |
|           | 10 | 32   | 160 | 16   | 80  | 16  |      |     |     |    | 224 |        |      |    |     |     | 528       |
|           | AB |      |     | 32   | 32  |     | 496  |     |     | 16 |     | 5328   | 432  |    |     | 32  | 6368      |
|           | CD | 112  | 32  | 352  | 272 | 240 | 432  | 32  | 48  |    | 144 | 6336   | 7584 | 64 | 128 | 96  | 15,872    |
|           | E  | 160  |     |      | 128 |     |      |     |     |    |     |        |      |    |     |     | 288       |
|           | F  | 32   |     |      |     |     |      |     |     |    |     |        |      |    | 48  |     | 80        |
|           | G  |      |     |      |     |     |      |     |     |    |     | 16     |      |    |     | 16  | 32        |
| OA (2023) |    | 480  | 880 | 2720 | 960 | 896 | 8496 | 144 | 112 | 64 | 544 | 14,112 | 8304 | 96 | 224 | 192 | 38,224    |

**Table A3.** Development and changes of local climate zone types in Tongren City from 2016 to 2023 (ha).

| LCZ Types |    | 2023 |     |      |     |     |      |     |     |    |     |        |      |    |     |     | OA (2016) |
|-----------|----|------|-----|------|-----|-----|------|-----|-----|----|-----|--------|------|----|-----|-----|-----------|
|           |    | 1    | 2   | 3    | 4   | 5   | 6    | 7   | 8   | 9  | 10  | AB     | CD   | E  | F   | G   |           |
| 2016      | 1  | 16   |     |      |     |     |      |     |     |    |     |        |      |    |     |     | 16        |
|           | 2  | 16   | 272 |      | 32  | 32  |      |     |     |    |     |        |      |    |     |     | 352       |
|           | 3  |      | 224 | 1088 | 64  | 32  |      |     |     |    | 48  |        | 32   | 32 |     |     | 1520      |
|           | 4  | 64   | 64  |      | 176 | 16  |      |     |     |    | 16  |        | 16   |    |     | 16  | 384       |
|           | 5  |      | 96  | 160  | 16  | 224 |      |     |     |    |     |        |      |    |     |     | 496       |
|           | 6  | 16   | 16  | 464  | 48  | 256 | 7072 | 64  | 16  | 32 | 48  | 2288   | 608  |    | 32  | 16  | 10,976    |
|           | 7  |      |     |      |     |     | 32   |     |     |    |     |        |      |    |     |     | 32        |
|           | 8  | 32   | 32  | 128  | 64  |     |      |     | 48  | 16 |     |        | 16   |    |     |     | 336       |
|           | 9  |      |     | 32   |     |     |      |     |     |    |     |        |      |    |     |     | 32        |
|           | 10 | 64   | 80  |      | 64  |     |      |     |     |    | 80  |        |      |    |     |     | 288       |
|           | AB |      | 16  | 32   | 16  |     | 192  |     |     | 16 |     | 4656   | 464  |    |     | 32  | 5424      |
|           | CD | 224  | 64  | 816  | 464 | 336 | 1200 | 80  | 48  |    | 352 | 7168   | 7168 | 48 | 192 | 112 | 18,272    |
|           | E  | 32   | 16  |      | 16  |     |      |     |     |    |     |        |      |    |     |     | 64        |
|           | F  | 16   |     |      |     |     |      |     |     |    |     |        |      |    |     |     | 16        |
|           | G  |      |     |      |     |     |      |     |     |    |     |        |      |    |     | 16  | 16        |
| OA (2023) |    | 480  | 880 | 2720 | 960 | 896 | 8496 | 144 | 112 | 64 | 544 | 14,112 | 8304 | 96 | 224 | 192 | 38,224    |

Appendix B

Appendix B.1

Table A4. Accuracy test of local climate zones in Tongren City in 2016 based on the confusion matrix.

| Project                 |    | Actual Category |        |        |        |       |        |       |        |       |        |        |       |       |       |        | Weight | User Accuracy (%) |
|-------------------------|----|-----------------|--------|--------|--------|-------|--------|-------|--------|-------|--------|--------|-------|-------|-------|--------|--------|-------------------|
|                         |    | 1               | 2      | 3      | 4      | 5     | 6      | 7     | 8      | 9     | 10     | AB     | CD    | E     | F     | G      |        |                   |
| Classification category | 1  | 1               |        |        |        |       |        |       |        |       |        |        |       |       |       |        | 1      | 100.00            |
|                         | 2  |                 | 20     |        |        |       |        |       |        |       |        |        |       |       |       |        | 20     | 100.00            |
|                         | 3  |                 |        | 50     |        |       |        |       |        |       |        |        |       |       |       |        | 50     | 100.00            |
|                         | 4  |                 |        |        | 20     |       |        |       |        |       |        |        |       |       |       |        | 20     | 100.00            |
|                         | 5  |                 |        |        |        | 30    |        |       |        |       |        |        |       |       |       |        | 30     | 100.00            |
|                         | 6  |                 |        |        |        | 8     | 183    | 9     |        |       |        |        |       |       |       |        | 200    | 91.50             |
|                         | 7  |                 |        |        |        |       |        | 2     |        |       |        |        |       |       |       |        | 2      | 100.00            |
|                         | 8  |                 |        |        |        |       |        | 2     | 18     |       |        |        |       |       |       |        | 20     | 90.00             |
|                         | 9  |                 |        |        |        |       |        |       |        | 2     |        |        |       |       |       |        | 2      | 100.00            |
|                         | 10 |                 |        |        |        |       |        |       |        | 1     | 16     |        | 1     |       |       |        | 18     | 88.89             |
|                         | AB |                 |        |        |        |       |        |       |        |       |        | 1      |       |       |       |        | 1      | 100.00            |
|                         | CD |                 |        |        |        |       |        |       |        |       |        |        | 195   | 5     |       |        | 200    | 97.50             |
|                         | E  |                 |        |        |        |       |        | 5     |        | 5     |        |        | 6     | 232   | 2     |        | 250    | 92.80             |
|                         | F  |                 |        |        |        |       |        |       |        |       |        |        |       |       | 4     |        | 4      | 100.00            |
|                         | G  |                 |        |        |        |       |        |       |        |       |        |        |       |       |       | 1      | 1      | 100.00            |
| Weight                  |    | 1               | 20     | 50     | 20     | 38    | 183    | 18    | 18     | 8     | 16     | 1      | 202   | 237   | 6     | 1      | 819    |                   |
| Production accuracy (%) |    | 100.00          | 100.00 | 100.00 | 100.00 | 78.95 | 100.00 | 11.11 | 100.00 | 25.00 | 100.00 | 100.00 | 96.53 | 97.89 | 66.67 | 100.00 |        |                   |
| Overall accuracy (%)    |    |                 |        |        |        |       |        |       |        |       | 94.63  |        |       |       |       |        |        |                   |
| Kappa coefficient       |    |                 |        |        |        |       |        |       |        |       | 0.93   |        |       |       |       |        |        |                   |

Table A5. Accuracy test of local climate zones in Tongren City in 2020 based on the confusion matrix.

| Project                 |    | Actual Category |        |        |        |        |       |       |       |       |       |       |       |       |       |        | Weight | User Accuracy (%) |
|-------------------------|----|-----------------|--------|--------|--------|--------|-------|-------|-------|-------|-------|-------|-------|-------|-------|--------|--------|-------------------|
|                         |    | 1               | 2      | 3      | 4      | 5      | 6     | 7     | 8     | 9     | 10    | AB    | CD    | E     | F     | G      |        |                   |
| Classification category | 1  | 3               |        |        |        |        |       |       |       |       |       |       |       |       |       |        | 3      | 100.00            |
|                         | 2  |                 | 20     |        |        |        |       |       |       |       |       |       |       |       |       |        | 20     | 100.00            |
|                         | 3  |                 |        | 63     |        |        |       |       |       |       |       |       |       |       |       |        | 63     | 100.00            |
|                         | 4  |                 |        |        | 20     |        |       |       |       |       |       |       |       |       |       |        | 20     | 100.00            |
|                         | 5  |                 |        |        |        | 38     | 2     |       |       |       |       |       |       |       |       |        | 40     | 95.00             |
|                         | 6  |                 |        |        |        |        | 192   | 6     | 2     |       |       |       |       |       |       |        | 200    | 96.00             |
|                         | 7  |                 |        |        |        |        |       | 5     |       |       |       |       |       |       |       |        | 5      | 100.00            |
|                         | 8  |                 |        |        |        |        |       |       | 18    |       |       |       |       |       |       |        | 18     | 100.00            |
|                         | 9  |                 |        |        |        |        |       |       |       | 5     |       |       |       |       |       |        | 5      | 100.00            |
|                         | 10 |                 |        |        |        |        |       |       |       |       | 18    |       | 1     | 1     |       |        | 20     | 90.00             |
|                         | AB |                 |        |        |        |        |       |       |       |       |       | 2     |       |       |       |        | 2      | 100.00            |
|                         | CD |                 |        |        |        |        |       |       |       | 3     | 2     | 2     | 189   | 2     | 2     |        | 200    | 94.50             |
|                         | E  |                 |        |        |        |        |       |       | 5     | 2     | 4     |       |       | 183   | 6     |        | 200    | 91.50             |
|                         | F  |                 |        |        |        |        |       | 1     |       | 1     |       |       |       | 4     | 12    |        | 18     | 66.67             |
|                         | G  |                 |        |        |        |        |       |       |       |       |       |       |       |       |       | 5      | 5      | 100.00            |
| Weight                  |    | 3               | 20     | 63     | 20     | 38     | 194   | 12    | 25    | 11    | 24    | 4     | 190   | 190   | 20    | 5      | 819    |                   |
| Production accuracy (%) |    | 100.00          | 100.00 | 100.00 | 100.00 | 100.00 | 98.97 | 41.67 | 72.00 | 45.45 | 75.00 | 50.00 | 99.47 | 96.32 | 60.00 | 100.00 |        |                   |
| Overall accuracy (%)    |    |                 |        |        |        |        |       |       |       |       | 94.38 |       |       |       |       |        |        |                   |
| Kappa coefficient       |    |                 |        |        |        |        |       |       |       |       | 0.93  |       |       |       |       |        |        |                   |

Table A6. Accuracy test of local climate zones in Tongren City in 2023 based on the confusion matrix.

| Project                 |    | Actual Category |        |        |       |       |        |       |       |       |       |       |       |       |       |        | Weight | User Accuracy (%) |
|-------------------------|----|-----------------|--------|--------|-------|-------|--------|-------|-------|-------|-------|-------|-------|-------|-------|--------|--------|-------------------|
|                         |    | 1               | 2      | 3      | 4     | 5     | 6      | 7     | 8     | 9     | 10    | AB    | CD    | E     | F     | G      |        |                   |
| Classification category | 1  | 20              |        |        |       |       |        |       |       |       |       |       |       |       |       |        | 20     | 100.00            |
|                         | 2  |                 | 20     |        |       |       |        |       |       |       |       |       |       |       |       |        | 20     | 100.00            |
|                         | 3  |                 |        | 49     |       |       |        |       |       |       |       |       |       |       |       |        | 49     | 100.00            |
|                         | 4  |                 |        |        | 50    |       |        |       |       |       |       |       |       |       |       |        | 50     | 100.00            |
|                         | 5  |                 |        |        | 1     | 49    |        |       |       |       |       |       |       |       |       |        | 50     | 98.00             |
|                         | 6  |                 |        |        |       | 2     | 154    | 2     | 1     |       |       |       |       |       |       |        | 159    | 96.86             |
|                         | 7  |                 |        |        |       |       |        | 9     |       |       |       |       |       |       |       |        | 9      | 100.00            |
|                         | 8  |                 |        |        |       |       |        |       | 7     |       |       |       |       |       |       |        | 7      | 100.00            |
|                         | 9  |                 |        |        |       |       |        |       |       | 4     |       |       |       |       |       |        | 4      | 100.00            |
|                         | 10 |                 |        |        |       |       |        | 1     | 1     | 1     | 17    |       |       |       |       |        | 20     | 85.00             |
|                         | AB |                 |        |        |       |       |        |       |       |       |       | 11    |       |       |       |        | 11     | 100.00            |
|                         | CD |                 |        |        |       |       |        |       | 1     | 2     | 1     | 3     | 189   | 4     |       |        | 200    | 94.50             |
|                         | E  |                 |        |        |       |       |        |       | 3     | 2     | 2     |       | 2     | 187   | 4     |        | 200    | 93.50             |
|                         | F  |                 |        |        |       |       |        |       |       |       |       |       |       | 2     | 4     |        | 6      | 66.67             |
|                         | G  |                 |        |        |       |       |        |       |       |       |       |       |       |       |       | 14     | 14     | 100.00            |
| Weight                  |    | 20              | 20     | 49     | 51    | 51    | 154    | 12    | 13    | 9     | 20    | 14    | 191   | 193   | 8     | 14     | 819    |                   |
| Production accuracy (%) |    | 100.00          | 100.00 | 100.00 | 98.04 | 96.08 | 100.00 | 75.00 | 53.85 | 44.44 | 85.00 | 78.57 | 98.95 | 96.89 | 50.00 | 100.00 |        |                   |
| Overall accuracy (%)    |    |                 |        |        |       |       |        |       |       |       | 95.73 |       |       |       |       |        |        |                   |
| Kappa coefficient       |    |                 |        |        |       |       |        |       |       |       | 0.95  |       |       |       |       |        |        |                   |

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