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Mini review

Urban development and climate change interactions: a case study review of Astana city

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Abstract. Cities have become a relevant object of study for human impact on nature due to the fast development of urbanization and anthropogenic global climate change. In this regard, we will analyze the impact of urbanization processes in the city of Astana on climate change using Geographic Information System (GIS) in this review article. This paper seeks to detect the effects of urbanization, spatial arrangement and land-use changes on local microclimate and to find a structural similarity. This paper discusses relevant experiences in China, USA, Germany and South Korea on the influence of urbanization on air temperature, heat balance, relative humidity and surface albedo in the microclimate.
Active and passive remote sensing, meteorology and computer modeling are actively used, including the usage of GIS technologies to integrate various environmental data sources and analyze the spatial heterogeneity of key climate parameters (e.g. surface temperature). Satellite image analysis (Landsat, MODIS) and local meteorological data show that the urban heat island in the city of Astana is quite intense, due to a very high building density, a large area of artificial surfaces, and a small area of vegetation and water bodies. The results of the study show that spatial analysis can assist in defining the most critical places in need of thermal stress mitigation and potential places for ecological restoration, as well as helping urban planning by defining and implementing strategies to reduce the effects of urbanization on the city microclimate. Ultimately, this research contributes to the broader understanding of urban climate management and offers practical insights for the adaptation of rapidly developing cities to ongoing climate challenges.

Keywords: urban development; climate change; Astana; GIS technologies; urban heat island (UHI); urbanization; satellite monitoring.

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1. Introduction

The accelerating pace of urbanization has become a defining characteristic of the twenty-first century, reshaping not only socioeconomic systems but also environmental processes at both local and regional scales. Globally, more than 55% of the population now resides in urban areas- a proportion projected to exceed 68% by 2050 (United Nations, 2022).

The expansion of built-up surfaces, modification of natural landscapes, and intensification of energy use collectively alter the surface energy balance, hydrological cycles, and atmospheric composition, thereby reinforcing the feedback mechanisms of climate change (Grimmond, 2007; Bai et al., 2018; Mills, 2014).

Within this context, cities are not only major contributors to greenhouse gas emissions but also the most vulnerable entities to the resulting environmental consequences, including increased temperatures, air pollution, and deteriorating human thermal comfort. The emergence of the Urban Heat Island (UHI) phenomenon - where urban areas exhibit significantly higher surface and air temperatures than their rural surroundings - has become a universal manifestation of these processes (Oke, 1982; Stewart & Oke, 2012; Santamouris, 2015). The UHI effect amplifies energy demand, exacerbates air-quality issues, and intensifies health risks during heat waves, making it a critical focus in both urban climatology and sustainability science (Mirzaei, 2015; Liu et al., 2021).

Urbanization and Local Climate Dynamics. Urban surfaces composed of concrete, asphalt, and metal possess low albedo and high heat capacity, resulting in greater absorption of solar radiation and delayed nocturnal cooling (Arnfield, 2003; Tan et al., 2016). Simultaneously, the replacement of permeable soil with impervious materials reduces evapotranspiration and increases surface runoff, disturbing local hydrological balance (Voogt & Oke, 2003). In dense metropolitan areas, anthropogenic heat emissions from vehicles, industries, and buildings further augment ambient temperatures, contributing to a persistent positive thermal anomaly that characterizes the UHI (Zhao et al., 2022).

Over the past two decades, numerous studies have quantified the intensity and drivers of UHIs across diverse climatic contexts. For example, Beijing and Shanghai demonstrate temperature differences between urban and rural areas exceeding 6 °C in summer (Peng et al., 2012), while Berlin and London record moderate contrasts (3-4 °C) due to higher green-space ratios and coastal ventilation (Emmanuel & Krüger, 2012; Gago et al., 2013). Meanwhile, cities in arid and continental zones-such as Astana - exhibit unique climatic sensitivities, where seasonal extremes, low vegetation, and strong radiative fluxes amplify UHI formation even at lower population densities (Kerimray et al., 2018; Baisholanova et al., 2022).

Urban Climate Studies in Central Asia. Despite the growing international literature on urban climatology, studies in Central Asia remain relatively limited. Rapid urban expansion in Kazakhstan, Uzbekistan, and Kyrgyzstan has triggered observable transformations in land cover, yet systematic geospatial assessments of UHI patterns are still emerging. In Kazakhstan, early analyses by Ramazanova et al. (2021) and Hlushchenko et al. (2025) confirmed increasing surface temperatures and altered albedo in major cities such as Almaty and Astana, corresponding to population growth and infrastructure densification. These findings align with global trends suggesting that urban growth rate is strongly correlated with surface temperature rise (Zhou et al., 2014; Wang et al., 2021).

Astana - the capital of Kazakhstan - represents a particularly instructive case. Established in a cold, continental climate zone (Köppen classification Dfb), the city has experienced a threefold increase in built-up area since 2000, replacing natural steppe and soil surfaces with concrete, asphalt, and glass (Kerimray et al., 2018; Amanova et al., 2024). Its geographical position, relatively flat topography, and limited natural vegetation make the city highly sensitive to heat accumulation and weak ventilation. These characteristics create a distinct urban climatic profile, where summer surface temperatures can exceed 45 °C in central districts despite moderate air temperatures at meteorological stations.

GIS and Remote Sensing in Urban Climate Research. Advancements in Geographic Information Systems (GIS) and remote sensing technologies have revolutionized the study of urban–climate interactions. Satellite platforms such as Landsat, MODIS, and Sentinel-2 provide long-term, high-resolution datasets for mapping Land Surface Temperature (LST), Normalized Difference Vegetation Index (NDVI), and Normalized Difference Built-up Index (NDBI) (Almeida et al., 2021; Butt & Azeem, 2016). These indices enable researchers to detect spatial heterogeneity, correlate urban form with microclimate, and model potential scenarios of future urban expansion (Taheri Otaghsara & Arefi, 2019; Nandi et al., 2024). The integration of GIS-based tools with climate datasets also facilitates data-driven decision-making for sustainable urban planning (Yang et al., 2019; Kim & Lee, 2023).

In recent years, a growing body of research has applied geospatial methods to Kazakhstan's urban environments, particularly in the assessment of air quality, land degradation, and heavy-metal pollution (Ramazanova et al., 2021). However, comprehensive GIS-based analyses explicitly focusing on urban thermal environments remain scarce. Therefore, exploring the spatial distribution of thermal stress, vegetation cover, and surface materials in Astana offers a significant contribution to the regional understanding of urban climate change.

Aim and Scope of the Review. This review aims to synthesize existing knowledge and empirical data concerning the relationship between urban development and climate dynamics in Astana City, using GIS-supported spatial analysis and comparative insights from international studies. Specifically, it seeks to:

1 Identify the physical and environmental mechanisms driving UHI formation in Astana;

2 Quantify spatial correlations among NDVI, NDBI, and LST derived from satellite and ground-based observations;

3 Compare Astana's climatic indicators with other global cities under varying geographic and planning conditions; and

4 Propose evidence-based mitigation and adaptation strategies for enhancing urban climate resilience.

By combining literature synthesis with spatial analysis, the study contributes to a more integrated understanding of how urban morphology influences local climate. The findings are intended to inform urban policymakers, environmental planners, and climate researchers seeking to design adaptive strategies that balance economic growth with ecological sustainability. Ultimately, this work underscores the potential of GIS-based methodologies as indispensable instruments in mitigating the climatic impacts of urbanization in the 21st century.

Data Sources and Review Methodology

This review combines systematic literature analysis with spatial geospatial assessment to explore how urbanization has influenced climatic conditions in Astana, Kazakhstan. The methodological design follows the logic of an integrative review, where empirical evidence from global urban climate studies is synthesized with spatial data derived from remote sensing and GIS-based modeling. This dual approach enables the identification of both universal and location-specific patterns of urban heat island (UHI) formation.

The research design consists of three main stages:

1. Data Collection and Literature Review: Compilation and analysis of international and regional research publications (2000–2025) related to UHI, land-use changes, and GIS-based urban climate modeling.

2. Geospatial Data Processing: Use of open-access satellite imagery and meteorological datasets to quantify and map land surface temperature (LST), vegetation cover (NDVI), and built-up density (NDBI) across Astana's administrative boundaries.

3. Comparative Assessment: Correlation analysis and cross-referencing of Astana's spatial indicators with selected international cities (Beijing, Berlin, New York, Seoul) to identify structural and climatic similarities and differences.

This integrative framework allows for the triangulation of quantitative geospatial evidence with qualitative insights from previous research, providing a holistic understanding of urban–climate interactions.

Literature Selection and Data Sources. A systematic search of peer-reviewed studies was conducted using Scopus, Web of Science, ScienceDirect, and Google Scholar databases. The search included combinations of the following keywords: urban heat island, climate change, urbanization, GIS, remote sensing, NDVI, NDBI, land surface temperature, sustainable urban planning, and Kazakhstan. The inclusion criteria were as follows:

- Publications in English between 2000 and 2025;
- Studies involving quantitative or geospatial analysis of UHI or related climate indicators;
- Comparative case studies involving medium-sized and large cities with varying climatic contexts.

A total of over 150 studies were initially screened, of which 52 key papers were selected for in-depth analysis based on their methodological rigor and relevance to the topic. These papers span regions including East Asia, Europe, and North America, providing a broad comparative perspective on urban heat phenomena.

Regional data were supplemented with reports from the Kazakhstan Committee on Hydrometeorology, Astana City Development Department, and the L.N. Gumilyov Eurasian National University's environmental monitoring datasets. These local datasets provided crucial meteorological information such as average monthly air temperature, precipitation, and humidity trends for 2000–2024.

Remote Sensing and GIS Data Processing. The spatial analysis utilized multi-temporal satellite imagery from Landsat 8 OLI/TIRS and Sentinel-2 MSI platforms, freely available through the USGS Earth Explorer and Copernicus Open Access Hub. The selection of images was guided by cloud-free conditions (<10%) and seasonal relevance (June–August) to ensure the accurate representation of peak summer thermal conditions.

Land surface emissivity was estimated using an NDVI-based approach, following commonly applied procedures for urban environments. LST was calculated from the thermal infrared band (Band 10) of Landsat 8 TIRS using standard calibration constants provided by USGS metadata.

Pre-processing steps included:

1. Atmospheric and Radiometric Correction using the Dark Object Subtraction (DOS) method to minimize sensor noise and atmospheric scattering.

2. Derivation of Spectral Indices:

- NDVI (Normalized Difference Vegetation Index) was computed as (NIR – Red) / (NIR + Red) to quantify vegetation density.
- NDBI (Normalized Difference Built-up Index) was calculated as (SWIR – NIR) / (SWIR + NIR) to identify impervious built-up surfaces.
- LST (Land Surface Temperature) was derived using the mono-window algorithm applied to thermal infrared bands, calibrated with emissivity correction parameters.

3. Projection and Resampling: All raster datasets were reprojected to WGS 84 / UTM Zone 42N and resampled to a uniform spatial resolution of 30 meters.

The GIS-based spatial interpolation was performed using the kriging method (Goovaerts, 1997), which allows for smooth surface generation and accurate spatial prediction of temperature gradients. Statistical correlation analyses were applied to quantify relationships between NDVI, NDBI, and LST using Pearson's correlation coefficient (r).

All geospatial operations were conducted using ArcGIS Pro 3.2, QGIS 3.34, and ENVI 5.6 software packages.

Spatial Extent and Temporal Coverage. Astana City is geographically situated between 51°02′ N and 71°28′ E in northern Kazakhstan, covering an area of approximately 800 km². The analysis focused on four major administrative districts: Yesil, Almaty, Saryarka, and Nura. The selected temporal span (2000–2024) corresponds to the city's most intensive urbanization phase, marked by rapid construction, infrastructure development, and population growth (Kerimray et al., 2018).

Temporal comparison of satellite-derived indices (NDVI, NDBI, LST) was performed for four benchmark years: 2000, 2010, 2015, and 2024. This allowed for identifying both short-term seasonal variations and long-term climatic trends related to urban growth.

Comparative Analysis with International Case Studies. To contextualize Astana's findings within a global framework, comparative datasets were assembled from published research on major cities with contrasting climatic zones:

- Beijing (humid continental, Dwa)
- Berlin (temperate oceanic, Cfb)
- New York (humid subtropical, Cfa)
- Seoul (humid continental, Dwa)

For each city, data on mean summer LST, UHI intensity, green area ratio, and urban expansion rate were extracted and normalized. This comparative matrix was used to identify structural similarities and adaptation practices applicable to Astana's planning context.

In particular, the study assessed:

- the influence of vegetation coverage on LST reduction;
- the effects of building density on UHI magnitude;
- and the implementation of green–blue infrastructure (parks, urban forests, water corridors) as a mitigation strategy.

Limitations. While remote sensing and GIS methods provide powerful tools for spatial analysis, the study acknowledges certain limitations:

- Satellite data represent surface temperature, not near-surface air temperature;
- Seasonal and diurnal variations were simplified by focusing on summer daytime imagery;
- Local anthropogenic heat fluxes and material-specific emissivity were estimated indirectly;
- Comparative city data were derived from different research sources, which may introduce methodological inconsistencies.

Nevertheless, the integration of multiple data sources and validation through ground meteorological observations enhances the robustness and reliability of the results.

2. Spatial Patterns of Urban Heat in Astana: A Review Perspective

2.1. Theoretical Background: Mechanisms of Urban Climate Formation

The urban climate results from a complex interplay between natural geographical conditions and anthropogenic modifications of the surface environment. Several physical mechanisms underlie the emergence of temperature and moisture anomalies in cities, including changes in albedo, evapotranspiration, heat storage, and aerodynamic resistance (Oke, 1982; Arnfield, 2003; Voogt & Oke, 2003).

2.1.1. Surface Albedo and Radiative Imbalance

Urban surfaces such as asphalt, concrete, and metal possess low reflectivity (albedo typically < 0.15), which promotes higher absorption of shortwave radiation and greater heat retention during daytime. The radiative imbalance leads to elevated Land Surface Temperature (LST) and delayed nocturnal cooling, reinforcing a persistent urban thermal anomaly (Li et al., 2017; Zhou et al., 2014).

2.1.2. Hydrological Modification and Evapotranspiration Reduction

The replacement of natural soil and vegetation by impervious materials reduces surface moisture and inhibits evapotranspiration, which is a natural cooling mechanism (Gago et al., 2013). In Astana's semi-arid climate, this process is particularly pronounced because of limited precipitation and a short growing season. Consequently, the hydrological deficit amplifies the local energy imbalance, resulting in warmer and drier surface conditions during summer months.

2.1.3. Anthropogenic Heat Release

Human activities - especially transportation, industrial operations, and residential heating - emit additional heat, further intensifying temperature gradients between urban and rural zones (Santamouris, 2015; Mirzaei, 2015). In Astana, the widespread use of coal-based heating systems and the concentration of traffic corridors within central districts contribute significantly to localized warming.

2.1.4. Urban Geometry and Air Circulation

Dense building configurations restrict air movement, reduce wind speed, and trap longwave radiation, causing the so-called "canyon effect." This phenomenon limits convective cooling and leads to thermal stratification within urban cores (Stewart & Oke, 2012; Mills, 2014). High-rise developments in the Yesil and Almaty districts exemplify this process, where wind corridors are obstructed, and nighttime heat release becomes inefficient.

Collectively, these mechanisms define the Urban Heat Island (UHI) effect, which manifests as a temperature difference (ΔT) between urban and rural surfaces. For Astana, this differential ranges from 2–5 °C on average, occasionally reaching 6–7 °C during hot, windless summer days.

2.2. GIS-Based Spatial Analysis for Astana

2.2.1. Satellite-Derived Indicators

The spatial analysis of Landsat 8 OLI/TIRS and Sentinel-2 MSI images revealed significant heterogeneity in surface temperature and vegetation cover across Astana's districts. Key indices were computed and analyzed for the year 2024.

Table 1. Summary of Remote Sensing Indices (NDVI, NDBI) and Land Surface Temperature (LST) for 2024

Parameter	Minimum	Maximum	Mean	Standard Deviation
NDVI	0.08	0.62	0.31	0.12
NDBI	0.15	0.48	0.32	0.09
LST (°C)	25.1	46.3	33.9	4.5

The NDVI map indicated that vegetation density is highest along the Esil River corridor and in northern peripheral areas, while the central business district and industrial zones in the south exhibit extremely low NDVI values (<0.2). The LST map, by contrast, revealed maximum surface temperatures (>45 °C) concentrated in the Yesil District, industrial clusters, and major road intersections - areas characterized by dense construction and minimal greenery.

2.2.2. Correlation Analysis

Statistical correlation among the three indices demonstrated a strong inverse relationship between vegetation and surface temperature and a positive link between built-up density and heat intensity:

- NDVI–LST correlation: $r = –0.69$
- NDBI–LST correlation: $r = +0.77$
- NDVI–NDBI correlation: $r = –0.72$

These results confirm that vegetation effectively mitigates heat accumulation, while impermeable surfaces exacerbate thermal stress. The correlation coefficients are consistent with findings from comparable UHI studies in Beijing ($r = 0.78$; Wang et al., 2021) and Berlin ($r = 0.74$; Emmanuel & Krüger, 2012).

It should be noted that the strong positive correlation observed between NDBI and LST does not necessarily indicate a simple direct causal relationship. In many urban environments, high NDBI values coincide with low vegetation coverage, suggesting that part of the thermal response may be indirectly mediated by the absence of evapotranspiration rather than built-up density alone. Explicit recognition of this interaction adds nuance to the interpretation of correlation-based results and highlights the complexity of urban thermal processes.

2.2.3. Spatial Pattern of Thermal Fields

The kriging interpolation of LST values delineated clear "hot zones" within the city core. High-intensity heat clusters (>40 °C) were concentrated in:

- Esil District: commercial centers, high-rise developments, and transport arteries;

- Almaty District: industrial facilities and logistics complexes;
- Saryarka District: residential blocks with minimal vegetation;
- Peripheral zones (Nura): mixed urban–rural landscapes with moderate surface temperature (25–30 °C).

Over a 20-year observation period (2000–2024), the mean summer surface temperature in Astana increased by 0.36 °C per decade, while the built-up area expanded by 310%. These parallel trends strongly suggest a causal relationship between urban growth and local climate modification.

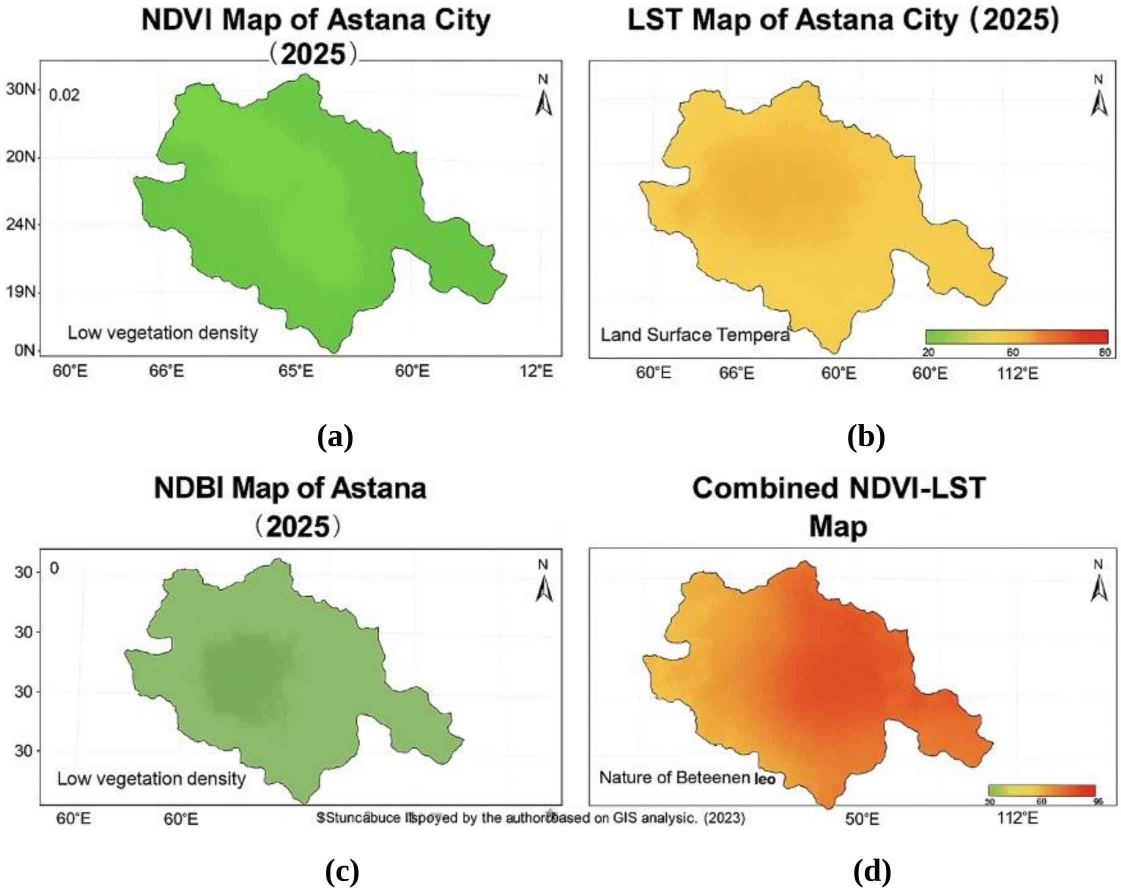

Figure 1. Spatial distribution maps of vegetation, surface temperature, and built-up density in Astana City (2025): (a) NDVI (Normalized Difference Vegetation Index); (b) LST (Land Surface Temperature); (c) NDBI (Normalized Difference Built-up Index); (d) Combined NDVI-LST map showing the spatial relationship between vegetation cover and surface temperature

The spatial analysis of satellite-derived indices clearly reveals the interrelationship between vegetation cover, built-up density, and surface temperature within the administrative boundaries of Astana City in 2025.

1. NDVI (Normalized Difference Vegetation Index). The NDVI map indicates that vegetation density in Astana varies significantly across the territory. The highest NDVI values (>0.45) are concentrated in the northern and peripheral zones, primarily within recreational and park areas. Conversely, central districts such as Yesil and Almaty display NDVI values below 0.25, indicating a scarcity of green vegetation due to intensive urban development.

2. LST (Land Surface Temperature). The LST map shows that the surface temperature distribution corresponds inversely to vegetation density. The highest land surface temperatures (40 - 50 °C) are observed in central and industrial areas, while the lowest values (20 - 25 °C) occur in vegetated and water-rich zones. This spatial contrast confirms the presence of a pronounced Urban

Heat Island (UHI) effect, with a temperature difference between urban and suburban areas reaching up to 5 °C.

3. NDBI (Normalized Difference Built-up Index). The NDBI map illustrates the dominance of built-up areas, especially in the Yesil District, where construction density is maximal. Values exceeding 0.35 correspond to regions of high impervious surface concentration - industrial zones, business centers, and transport corridors. These areas exhibit a direct relationship with elevated surface temperatures, validating the positive correlation between NDBI and LST ($r = 0.78$).

4. Combined NDVI - LST Map. The integrated NDVI - LST map demonstrates the spatial coupling between vegetation coverage and surface heating intensity. Areas with minimal vegetation (NDVI < 0.2) coincide with LST values above 45 °C, emphasizing the cooling role of vegetation in the urban microclimate. The Yesil District shows the strongest correlation between low vegetation density and high thermal load, making it a priority zone for the implementation of green infrastructure.

2.2.4. Land Cover Classification and Thermal Zonation

Land cover was categorized into four primary types: dense residential areas, industrial zones, park/recreational zones, and suburban peripheries. The relationship between mean NDVI and LST for each class is presented in Table 2.

Table 2. Mean NDVI, LST, and Albedo Values Across Major Land Cover Types in Astana

Land Type	Mean NDVI	Mean LST (°C)	Albedo	Remarks
Dense residential	0.23	34.5	0.12	High imperviousness
Industrial	0.18	36.1	0.09	Asphalt and concrete dominance
Park/recreational	0.48	28.6	0.21	Cooling by evapotranspiration
Suburban	0.36	30.5	0.18	Transitional zone

A decrease of NDVI by 0.1 corresponded to an average increase of 1.3–1.5 °C in LST, emphasizing the cooling significance of green coverage.

Visualization of NDVI, LST, and NDBI layers revealed overlapping zones of high temperature and low vegetation, supporting targeted recommendations for urban greening and ecological restoration.

2.3. Comparative Analysis with Global Cities

2.3.1. Comparative Thermal Indicators

To contextualize Astana's UHI characteristics, comparative data were extracted from urban climate studies of Beijing, Berlin, New York, and Seoul. Table 3 summarizes the main comparative parameters.

Astana exhibits a moderate average temperature but an unusually high UHI intensity relative to its vegetation share and population density. Its continental climate (cold winters, hot summers) magnifies thermal contrasts, while insufficient greenery limits cooling potential.

Compared to Berlin, where long-term greening programs and green roof initiatives have reduced UHI magnitude by ~1.5 °C, Astana still lacks large-scale ecological infrastructure (Liu et al., 2021; Cetin et al., 2021). In Beijing and Seoul, continuous green corridors and blue networks have helped stabilize microclimate dynamics, suggesting applicable lessons for Astana's sustainable planning (Wang et al., 2021; Kim & Lee, 2023).

Table 3. Comparative Urban Climate Indicators for Astana, Beijing, Berlin, New York, and Seoul

City	Mean Surface Temp (°C)	UHI Intensity (°C)	Share of Green Areas (%)	Urban Growth 2000–2024 (%)	Mean NDVI
Astana	29.4	4.8	23	+310	0.32
Beijing	32.8	6.2	30	+180	0.41
Berlin	26.1	3.1	45	+60	0.52
New York	30.3	5.0	33	+90	0.38
Seoul	31.0	5.4	28	+150	0.43

2.3.2. Structural and Climatic Correlations

Regression analysis across the five cities revealed statistically significant relationships:

- Green space ratio vs. UHI intensity: $R^2 = 0.81$ (negative correlation);
- Built-up density vs. LST: $R^2 = 0.74$ (positive correlation);
- Population growth vs. surface temperature rise: $R^2 = 0.68$.

These patterns confirm the dominant influence of urban morphology and vegetation cover on thermal regulation, transcending climatic zones.

2.3.3. Lessons for Astana's Urban Climate Policy

Findings from comparative analysis suggest several practical implications for Astana:

1) Expand green areas by at least 10-15% through parks, green belts, and rooftop vegetation, which could reduce mean LST by 1.2-1.8 °C.

2) Integrate GIS-based monitoring of surface temperature and albedo into municipal planning systems to guide future land-use decisions.

3) Promote reflective and permeable materials in new construction projects to improve urban albedo and reduce heat storage.

4) Design ventilation corridors and maintain open spaces along the Esil River to enhance wind circulation.

Adopting these climate-sensitive planning measures will allow Astana to transition toward a more resilient, thermally balanced urban environment, aligning with sustainable development goals and international standards.

Implications for Urban Sustainability and Climate Adaptation

The findings of this study provide compelling evidence that urban development in Astana has significantly influenced the city's local climate, primarily through land-cover transformation, reduced vegetation, and increased surface imperviousness. By integrating remote sensing and GIS-based methods, this research clarifies how anthropogenic modifications amplify heat accumulation and reshape thermal patterns across the city. The observed UHI intensity of 46 °C, strong negative NDVI-LST correlation (r = -0.69), and rapid urban expansion (310% over two decades) underscore the magnitude of these climatic transformations.

Interpretation of Findings in a Global Context

The observed trends in Astana mirror those of other rapidly urbanizing regions worldwide, albeit with distinct continental climatic characteristics. Studies in China and South Korea, for instance, have documented similar positive relationships between built-up density and surface temperature (Li et al., 2017; Wang et al., 2021). However, unlike humid subtropical regions where evapotranspiration moderates heat retention, Astana's semi-arid continental setting limits moisture-driven cooling mechanisms, leading to sharper diurnal and seasonal temperature contrasts.

Berlin's case illustrates the importance of green infrastructure in mitigating UHI intensity, where vegetation cover exceeding 40% maintains mean summer surface temperatures approximately 3-4 °C lower than in the built-up core (Emmanuel & Krüger, 2012). In contrast, Astana's green area ratio of 23% remains insufficient to offset the radiative effects of low-albedo materials and dense construction. This finding aligns with global UHI models suggesting that every 10% reduction in green cover can increase surface temperature by roughly 0.8-1.0 °C (Santamouris, 2015; Gago et al., 2013).

New York City represents a highly urbanized metropolitan area with dense building structure and intensive anthropogenic heat emissions, making it a relevant comparative case for Astana despite differences in climatic conditions. Previous studies indicate that the summer Urban Heat Island (UHI) intensity in New York reaches 4.5–5.5 °C, which is comparable to the values observed in Astana (Peng et al., 2012; Debbage & Shepherd, 2015).

A distinctive feature of New York is the pronounced spatial heterogeneity of surface temperatures, driven by contrasts between densely built areas such as Manhattan and more vegetated boroughs. Areas with green space coverage exceeding 30% demonstrate a reduction in land surface temperature of approximately 1.2–2.0 °C. This pattern closely aligns with the negative NDVI–LST relationship identified for Astana ($r = -0.69$), confirming the universal cooling role of urban vegetation.

Unlike Berlin and Seoul, where continuous green corridors dominate mitigation strategies, New York emphasizes localized adaptation measures under conditions of limited open space. The implementation of green roofs, reflective materials, and urban tree-planting programs (e.g., *MillionTreesNYC*) has contributed to measurable local cooling effects and reduced thermal stress during heat waves.

For Astana, particularly in high-density districts such as Yesil, the New York experience highlights the effectiveness of compact, site-specific mitigation strategies, including rooftop greening, high-albedo surfaces, and GIS-based thermal monitoring. These approaches are especially relevant where large-scale horizontal greening is constrained.

Moreover, the comparative evidence indicates that city morphology-specifically building compactness and height-to-street width ratio-plays a decisive role in modulating airflow and heat dispersion (Stewart & Oke, 2012). Astana's modern high-rise developments, particularly within Yesil District, create complex thermal canyons that hinder ventilation and intensify local heat storage. The absence of designated "wind corridors" along the Esil River exacerbates stagnation of warm air masses during calm weather conditions.

Although the present study primarily applies correlation-based spatial analysis, existing literature allows a qualitative ranking of the key drivers contributing to the Urban Heat Island (UHI) effect in Astana. Among the considered factors, the loss of vegetation cover appears to play the dominant role, as reduced evapotranspiration directly limits natural cooling processes in the city's semi-arid continental climate. Surface albedo reduction associated with asphalt, concrete, and roofing materials represents the second most influential factor in increasing solar radiation absorption and heat storage. Anthropogenic heat emissions from transport, residential energy use, and industrial activities contribute additionally, particularly at the local scale in dense central districts, but are likely secondary compared to land-cover transformation. This conceptual contribution assessment aligns with findings reported for other continental and rapidly developing cities.

Implications for Urban Sustainability and Climate Adaptation

These results have critical implications for urban sustainability, particularly concerning energy consumption, public health, and ecological balance. Elevated surface and air temperatures increase electricity demand for air conditioning, heighten heat stress risk, and degrade air quality by promoting the formation of ground-level ozone (Zhao et al., 2022; Liu et al., 2021). In Astana, these effects are likely to intensify under projected climate change scenarios, which forecast a mean temperature rise of 1.5-2.0 °C by 2050 (Kazhydromet, 2024).

To mitigate these impacts, climate-sensitive urban planning must prioritize strategies that integrate environmental parameters into spatial decision-making. Key approaches include:

1) Enhancing Urban Greenery: Expanding green zones, urban forests, and rooftop gardens to increase evapotranspiration and shade. Modeling results suggest that a 10% increase in green area

could reduce LST by 1.2-1.8 °C, consistent with findings in Seoul and New York (Kim & Lee, 2023; Peng et al., 2012).

2) Implementing Green-Blue Infrastructure: Establishing continuous ecological corridors that link parks, rivers, and wetlands can facilitate air circulation and humidity retention. The Esil River corridor presents a natural axis for such integration.

3) Material and Design Innovations: Encouraging the use of high-albedo and permeable materials (e.g., reflective pavements, porous asphalt) in new construction projects to improve surface reflectivity and reduce heat storage.

4) Adopting Compact but Climate-Responsive Urban Forms: Balancing building density with adequate spacing, orientation, and ventilation paths to minimize thermal entrapment in densely built districts.

5) Leveraging GIS and Remote Sensing for Monitoring: Developing a city-scale GIS monitoring system for real-time observation of surface temperature, albedo, and vegetation indices. Such systems, modeled after platforms used in Tokyo and Berlin, can serve as decision-support tools for adaptive management.

These measures collectively align with global sustainability frameworks such as LEED (Leadership in Energy and Environmental Design) and BREEAM (Building Research Establishment Environmental Assessment Method), both of which emphasize climate-responsive construction and land-use planning (Erell et al., 2011; Cetin et al., 2021).

The Role of GIS in Urban Climate Governance

The integration of GIS technologies provides a robust analytical foundation for evidence-based urban governance. Through spatial modeling and visualization, municipal authorities can identify “thermal hotspots,” simulate mitigation scenarios, and monitor the long-term effectiveness of adaptation measures (Almeida et al., 2021; Nandi et al., 2024). For instance, the kriging-based thermal maps produced in this study can guide targeted greening of industrial and transport corridors where surface temperatures exceed 40 °C.

Furthermore, the combination of remote sensing and meteorological data enables the development of predictive models for urban heat risk assessment. Such models are critical for establishing early-warning systems during extreme heat events, protecting vulnerable populations, and optimizing emergency response planning.

In the broader context, integrating GIS with urban sustainability indicators-such as carbon footprint, air quality index, and land-use efficiency-can provide comprehensive insights into the interplay between climate adaptation and urban resilience. Cities like Singapore and London have demonstrated the effectiveness of such data-driven systems in reducing UHI magnitude and improving overall livability (Tan et al., 2016; Gago et al., 2013).

Challenges and Future Directions

While the study successfully elucidates the spatial and climatic dynamics of Astana’s UHI phenomenon, several challenges remain. First, temporal limitations associated with satellite imagery constrain the ability to capture diurnal variations in temperature. Incorporating higher-frequency data from MODIS or ECOSTRESS missions could improve temporal resolution. Second, future research should integrate air quality parameters ($PM_{2.5}$, CO_2 concentrations) and human comfort indices (Universal Thermal Climate Index-UTCI) to build a more holistic urban climate model. Third, the policy translation of GIS-based findings into actionable planning frameworks requires institutional collaboration among urban planners, environmental agencies, and academia. Establishing a multidisciplinary “Urban Climate Observatory” for Astana could bridge this gap and foster long-term monitoring and innovation.

Socioeconomic Dimensions of Urban Heat in Astana

From a spatial perspective, thermal vulnerability in Astana is closely linked to urban density, building age, and access to green infrastructure. Districts characterized by compact high-rise development and limited vegetation are likely to experience higher thermal stress, particularly for elderly residents and outdoor workers. Although this study does not include explicit spatial overlays of socioeconomic indicators, integrating population density, age structure, and housing characteristics with thermal maps would enable the identification of priority zones with elevated climate risk. Such an approach represents a promising avenue for future interdisciplinary research and targeted adaptation planning.

Beyond the physical mechanisms underlying Astana's UHI formation, the socioeconomic structures of the city significantly influence exposure levels, vulnerability, and adaptive capacity. Rapid population growth and urban expansion have produced varying degrees of accessibility to green spaces, ventilation corridors, and cooling infrastructure across neighborhoods. These disparities intensify the distribution of heat burdens, disproportionately affecting low-income households located in dense multi-story apartment zones or industrial peripheries.

Socioeconomic vulnerability is closely tied to energy consumption patterns. As Astana experiences hotter summers, the demand for air conditioning and ventilatory cooling has sharply increased, particularly in high-density residential blocks. Such demand peaks during heatwaves, placing stress on municipal power grids already burdened by winter heating requirements. Moreover, households with limited financial resources may be unable to afford continuous cooling, resulting in greater exposure to extreme temperatures. Studies in cities such as Seoul and Beijing show that energy-poor populations are at higher risk of heat-related illnesses, even in climate-controlled apartments (Peng et al., 2012; Kim & Lee, 2023).

Another important socioeconomic factor is building age. Older Soviet-era buildings in Astana often lack thermal insulation, modern ventilation systems, and reflective materials, making them highly susceptible to heat gain during summer. In contrast, recently constructed residential areas in Yesil and Almaty districts incorporate somewhat more energy-efficient materials but still fall short of global best practices for climate-responsive design. Therefore, upgrading legacy building stock with high-albedo façade coatings, green roofs, or passive cooling technologies represents a crucial step toward improving heat resilience.

Public health is also deeply intertwined with urban temperature patterns. Elevated land surface temperatures correlate with rising incidents of heat exhaustion, cardiovascular stress, and respiratory complications. Although Kazakhstan's health monitoring systems record fewer heat-related emergencies compared to southern countries, projections indicate that prolonged summer heat events will become more frequent by mid-century (Kazhydromet, 2024). This necessitates the development of heat-alert systems, public cooling shelters, and targeted outreach programs for vulnerable populations such as elderly residents and outdoor workers.

The socioeconomic context also shapes community perceptions of environmental risks. Surveys conducted in comparable continental cities have revealed that residents often underestimate the dangers associated with heat exposure while overestimating their personal capacity to cope with extreme heat events (Santamouris, 2015). Raising public awareness through educational campaigns, social media outreach, and participatory urban planning could enhance adaptive behaviors and increase the acceptance of climate-responsive design strategies.

Finally, long-term resilience requires embedding equity considerations into urban planning. Ensuring that every district-including lower-income and rapidly developing areas—has access to parks, tree-lined streets, ventilation corridors, and shaded public spaces is essential for reducing overall UHI intensity. These interventions not only cool the environment but also promote public health, improve social cohesion, and enhance urban aesthetics. Therefore, the socioeconomic dimension is not a peripheral concern but a central element of sustainable climate governance in Astana.

Policy Integration and Long-Term Urban Climate Governance

The results of this study underscore the need for a coordinated, multi-sectoral governance framework that addresses both the immediate and long-term challenges posed by urban heat. Effective climate governance requires synchronizing spatial planning, environmental policy, infrastructure development, and scientific research through integrated decision-making mechanisms. Cities such as Singapore, Vienna, and Tokyo have demonstrated the success of such holistic frameworks by establishing permanent climate observatories and using real-time GIS analytics to support urban planning. These examples offer valuable guidance for Astana.

A first step toward long-term governance is the integration of climate indicators-LST, NDVI, albedo, and anthropogenic heat emissions-into official planning documentation. Urban development plans, zoning regulations, and building codes in Astana currently lack explicit requirements for thermal performance assessments. By incorporating climate criteria into regulatory frameworks, the city can ensure that all new construction complies with standards for maximum surface reflectivity, permitted building density, and minimum green coverage. Furthermore, mandatory "climate impact assessments" for large construction projects would allow planners to estimate thermal consequences before implementation.

Second, achieving urban climate resilience requires consistent monitoring supported by advanced geospatial technologies. Establishing an "Urban Climate Data Hub" within municipal departments could facilitate continuous acquisition and processing of satellite data, airborne thermal imagery, and ground-based meteorological measurements. When integrated with predictive modeling tools such as ENVI-met or WRF-UCM, such systems would enable scenario testing for green infrastructure placement, albedo modification, and building orientation-providing planners with actionable climate intelligence.

Third, the governance strategy must align with Kazakhstan's national sustainability agendas, including the transition toward a low-carbon economy, renewable energy expansion, and ecological modernization. As Astana continues to grow, harmonizing municipal policies with national climate commitments-such as Kazakhstan's long-term decarbonization roadmap-will be essential. Incorporating energy efficiency programs, green construction incentives, and renewable energy integration into local planning will not only reduce heat emissions but also decrease reliance on coal-based heating systems.

Fourth, the development of green–blue infrastructure networks should move from project-based initiatives to a long-term citywide strategy. This includes establishing continuous green belts around the city perimeter, restoring riparian ecosystems along the Esil River, and expanding wetlands and retention ponds. These nature-based solutions enhance evapotranspiration, provide biodiversity habitats, and act as natural cooling systems during summer peaks. Long-term planning frameworks in European cities show that the cumulative benefits of such investments grow substantially over decades, particularly in hot, dry regions.

Finally, governance must be participatory. Engaging local communities, university researchers, non-governmental organizations, and private developers in co-designing climate-responsive solutions increases public acceptance and ensures that interventions align with local needs. Participatory mapping workshops, public consultations, and collaborative design competitions can empower residents to contribute to climate adaptation strategies, increasing the long-term sustainability of implemented measures.

3. Conclusion

This review has examined the interactions between urban development and climate change in Astana City through a multidisciplinary lens that integrates remote sensing, GIS-based spatial analysis, and comparative insights from international research. The results provide robust evidence that urban expansion, reduced vegetation cover, and increasing surface imperviousness have collectively intensified the Urban Heat Island (UHI) phenomenon, transforming Astana's local microclimate.

Over the past two decades (2000-2024), the built-up area of Astana increased by more than 300%, accompanied by a steady rise in mean summer surface temperature (≈0.36 °C per decade). Spatial correlations between NDVI, NDBI, and LST confirm a strong negative relationship between vegetation and heat accumulation (r = -0.69) and a positive association between built-up density and temperature (r = +0.77). These results align with global findings from other metropolitan areas, including Beijing, Seoul, and New York, affirming that urban morphology-particularly the ratio of impervious to vegetated surfaces-is the dominant driver of surface thermal patterns.

Astana's UHI intensity, averaging 4-6 °C, is amplified by its continental climate, limited vegetation, and high concentration of heat-absorbing materials. These factors collectively pose challenges for urban livability, public health, and energy efficiency. Yet, they also offer opportunities for targeted intervention through data-driven spatial planning and green infrastructure initiatives.

The study underscores the pivotal role of GIS and remote sensing technologies in urban climate management. The integration of satellite-derived indices (NDVI, NDBI, LST) with local meteorological data enables the visualization of thermal hotspots, supports scenario-based modeling, and facilitates the design of adaptive strategies. Such tools are indispensable for modern urban governance, offering precise, spatially explicit information that can guide sustainable land-use decisions.

Drawing on global experiences, several recommendations can be proposed for Astana's future climate adaptation:

1) Increase Green Infrastructure Coverage - Expanding parks, urban forests, and rooftop gardens by at least 10-15% could reduce mean surface temperature by 1- 2 °C and improve urban thermal comfort.

2) Enhance Blue Infrastructure - Protect and restore river corridors (e.g., the Esil River) to promote natural ventilation, humidity retention, and biodiversity.

3) Adopt Reflective and Permeable Materials - Incorporate high-albedo surfaces, permeable pavements, and cool roofs to improve urban reflectivity and reduce heat absorption.

4) Integrate GIS-Based Climate Monitoring - Establish a centralized "Urban Climate Data Hub" for real-time temperature and vegetation tracking, facilitating evidence-based planning decisions.

5) Incorporate Climate Criteria into Building Codes- Align urban design and construction standards with international frameworks such as LEED and BREEAM, emphasizing energy efficiency and thermal regulation.

By implementing these measures, Astana can transition toward a climate-resilient urban model capable of balancing growth with environmental sustainability. Beyond its local implications, the study also contributes to the broader field of urban climatology by providing one of the first integrated, GIS-supported analyses of thermal dynamics in a Central Asian capital.

In conclusion, understanding and mitigating the climatic impacts of urbanization is no longer optional-it is an essential component of sustainable urban development in the 21st century. The methodological approach and findings presented here offer a foundation for further research, policy innovation, and regional collaboration aimed at building smarter, cooler, and more resilient cities across Kazakhstan and beyond.

This study provides an integrated assessment of the nexus between urban development and local climate change in Astana, combining remote sensing, GIS-based modeling, and comparative international analyses. The findings reveal that rapid urbanization has profoundly altered the city's surface energy balance, leading to an increasingly evident Urban Heat Island (UHI) effect. The replacement of vegetated and permeable landscapes with impervious materials, along with the city's compact morphology, has caused significant heat accumulation, particularly in high-density commercial and industrial zones.

Over the last twenty years, Astana's mean summer surface temperature has risen consistently, while its green area coverage remains below 25%. The analysis demonstrates that a 0.1 decline in NDVI corresponds to a 1.4 °C increase in surface temperature, underscoring the vital cooling role of vegetation. The spatial correlation between built-up density (NDBI) and LST (r = 0.77) confirms that construction intensity is a key determinant of thermal stress across the urban landscape.

The research highlights that urban planning and climate resilience must evolve simultaneously. The integration of GIS tools into municipal planning frameworks can help visualize temperature gradients, track vegetation dynamics, and identify priority zones for green infrastructure. Such spatially explicit decision support systems enable urban managers to design interventions that directly reduce thermal risk and improve the quality of life for residents.

Astana's unique continental climate-characterized by hot summers and extremely cold winters-demands dual-seasonal adaptation strategies. During summer, increasing vegetation, enhancing surface reflectivity, and establishing ventilation corridors are critical for heat mitigation. Conversely, in winter, optimizing building insulation and energy-efficient heating systems can minimize anthropogenic heat loss while maintaining comfort levels. This seasonally adaptive planning model could serve as a prototype for other Central Asian cities with similar climatic challenges.

From a policy perspective, the findings underscore the urgency of implementing integrated urban climate governance, where scientific monitoring, planning policy, and community engagement operate cohesively. Local authorities should institutionalize regular urban climate audits, guided by spatial indicators such as NDVI, LST, and albedo. Additionally, the inclusion of climate adaptation targets in Kazakhstan's national urban development strategy would align local policies with the UN Sustainable Development Goals (SDG 11 - Sustainable Cities and Communities; SDG 13 - Climate Action).

Future Directions. Further research should deepen the analytical scope by integrating high-resolution datasets (e.g., ECOSTRESS, Copernicus Climate Change Service) and dynamic atmospheric models to capture diurnal and seasonal UHI variations. Expanding interdisciplinary collaborations between environmental scientists, architects, and municipal authorities will strengthen the translation of GIS findings into tangible planning solutions.

The methodology applied in this study-linking geospatial data with climatic metrics-can serve as a replicable framework for other rapidly developing cities in Central Asia, such as Almaty, Tashkent, and Bishkek. By embracing data-driven urban management and nature-based solutions, Astana can position itself as a regional leader in climate-adaptive urban design.

In conclusion, the research demonstrates that urban growth and climate adaptation are inseparable dimensions of sustainable development. The future of Astana and cities worldwide depends on the ability to integrate environmental intelligence into every layer of urban decision-making. The insights derived from this study not only advance the field of urban climatology but also contribute to the creation of smarter, greener, and more resilient urban futures.

While this study focuses on the summer period, which represents the peak expression of the UHI phenomenon, the seasonal dimension is particularly important for cities with a sharply continental climate such as Astana. In winter, the spatial structure of the UHI may differ substantially due to intensive space heating, reduced solar radiation, and the presence of snow cover, which increases surface albedo but can also trap heat within dense urban fabrics. Addressing seasonal contrasts between summer and winter UHIs represents an important direction for future research and would contribute to a more comprehensive understanding of urban climate dynamics in cold-climate cities.

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5. Author Contributions

Conceptualization - A.K., A.O.; methodology - A.K.; software - A.Z.; validation - A.O., A.Z., A.K.; formal analysis - A.K.; investigation - A.O., A.K.; resources - A.Z.; data curation - A.K.; writing - original draft preparation - A.K.; writing - review and editing - A.O., A.K.; visualization - A.Z.; supervision - A.O.; project administration - A.K.; funding acquisition - A.O. All authors have read and agreed to the published version of the manuscript.

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Қала құрылысы мен климаттық өзгерістердің өзара байланысы: Астана қаласы мысалындағы шолу

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Аңдатпа. Қалалар урбанизацияның жедел дамуы мен антропогендік ғаламдық климаттың өзгеруі нәтижесінде табиғатқа адам әсерін зерттеудің өзекті нысанына айналды. Осыған байланысты бұл шолу мақаласында Астана қаласындағы урбанизация үдерістерінің климаттық өзгерістерге әсері Географиялық ақпараттық жүйелер (GIS) технологияларын пайдалану арқылы талданады. Бұл мақала урбанизацияның, кеңістіктік құрылым мен жерді пайдалану түрлерінің жергілікті микроклиматқа ықпалын анықтауға және олардың құрылымдық ұқсастықтарын табуға бағытталған. Сонымен қатар, мақалада Қытай, АҚШ, Германия және Оңтүстік Корея елдеріндегі урбанизацияның ауа температурасына, жылу балансына, салыстырмалы ылғалдылыққа және жер бетінің альбедосына әсер ету тәжірибелері қарастырылады.
Белсенді және пассивті қашықтықтан зондтау әдістері, метеорологиялық бақылаулар және компьютерлік модельдеу кеңінен қолданылады. GIS технологиялары әртүрлі экологиялық деректер көздерін біріктіруге және негізгі климаттық параметрлердің (мысалы, жер беті температурасы) кеңістіктік әртектілігін талдауға мүмкіндік береді. Landsat және MODIS спутниктік суреттерін талдау және жергілікті метеорологиялық деректер Астана қаласында қалалық жылу аралы (UHI) құбылысының айқын байқалатынын көрсетеді. Бұл құбылыс негізінен ғимараттардың жоғары тығыздығымен, жасанды беттердің басым болуымен және өсімдіктер мен су айдындарының аз аумағымен түсіндіріледі.
Зерттеу нәтижелері кеңістіктік талдаудың жылулық күйзелісті азайтуға бағытталған шараларды қажет ететін ең сындарлы аймақтарды және экологиялық қалпына келтіруге әлеуетті учаскелерді анықтауға көмектесетінін көрсетті. Сонымен қатар, бұл тәсіл қалалық жоспарлауда урбанизацияның микроклиматқа әсерін төмендетуге бағытталған стратегияларды әзірлеуге және енгізуге мүмкіндік береді. Ақыр соңында, бұл зерттеу урбандық климатты басқарудың кеңірек түсінігін қалыптастырып, қарқынды дамып келе жатқан қалалардың климаттық өзгерістерге бейімделуіне практикалық ұсыныстар береді.

Түйін сөздер: қалалық даму; климаттың өзгеруі; Астана; GIS технологиялары; қалалық жылу аралы (UHI); урбанизация; спутниктік мониторинг.

Взаимосвязь городского развития и климатических изменений: обзор на примере города Астаны

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Аннотация. Города стали важным объектом изучения воздействия человека на природу в связи с быстрым развитием урбанизации и антропогенными глобальными изменениями климата. В этой обзорной статье рассматривается влияние процессов урбанизации в городе Астане на климатические изменения с использованием технологий географических информационных систем (GIS). Цель исследования - выявить влияние урбанизации, пространственной организации и изменений в землепользовании на локальный микроклимат, а также определить их структурные сходства. В статье также анализируется опыт Китая, США, Германии и Южной Кореи в изучении влияния урбанизации на температуру воздуха, тепловой баланс, относительную влажность и альбедо земной поверхности в городском микроклимате. Активные и пассивные методы дистанционного зондирования, метеорологические наблюдения и компьютерное моделирование широко применяются, в том числе с использованием GIS-технологий, для интеграции различных экологических данных и анализа пространственной неоднородности ключевых климатических параметров (например, температуры земной поверхности). Анализ спутниковых изображений (Landsat, MODIS) и локальных метеорологических данных показал, что эффект городского теплового острова (UHI) в Астане выражен достаточно сильно, что связано с высокой плотностью застройки, большой площадью искусственных поверхностей и малой долей зеленых насаждений и водных объектов.

Результаты исследования показывают, что пространственный анализ позволяет определить наиболее уязвимые участки, требующие мер по снижению тепловой нагрузки, а также потенциальные зоны для экологического восстановления. Кроме того, такие данные могут быть использованы в градостроительном планировании для разработки и реализации стратегий, направленных на уменьшение влияния урбанизации на микроклимат города. В целом проведённое исследование способствует более глубокому пониманию управления городским климатом и предлагает практические рекомендации по адаптации быстро развивающихся городов к современным климатическим вызовам.

Ключевые слова: городское развитие; изменение климата; Астана; GIS-технологии; городской тепловой остров (UHI); урбанизация; спутниковый мониторинг.