SPATIAL ANALYTICS OF CLIMATE CHANGE IMPACTS: THE CASE STUDY OF MARIBOR

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Climate change represents one of the most pressing challenges of the twenty-first century, marked by rising global temperatures, more frequent heatwaves, and increasing risks of floods and droughts. Urban areas are particularly vulnerable because dense construction, limited vegetation, and impervious surfaces intensify heat exposure and reduce resilience. This urban heat island effect has significant consequences for human health, infrastructure, and the environment, making cities critical focal points for adaptation strategies. This study explores long-term climate change in Slovenia with a focus on Maribor, the country's second-largest city. Maribor's geographical location in the Drava valley, combined with its ageing population, increases its vulnerability to extreme heat events. Evidence indicates a seasonal shift in urban heat intensity from colder to warmer months, with projections of substantial increases in future decades, particularly in industrial zones. By combining high-resolution climate data, satellite imagery, and socio-demographic indicators, this research identifies spatial patterns of heat stress and highlights vulnerable areas. The findings provide a scientific basis for sustainable urban planning and effective adaptation to climate change.

Keywords:
GIS,
urban heat island,
urban planning,
heat stress,
health risks

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PROSTORSKA ANALITIKA VPLIVOV PODNEBNIH SPREMEMB: ŠTUDIJA PRIMERA MARIBOR

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Ključne besede:
GIS,
mestni toplotni otok,
urbano načrtovanje,
toplotni stress,
zdravstvena tveganja

Podnebne spremembe predstavljajo enega najresnejših izzivov enaindvajsetega stoletja, za katere so značilni naraščanje globalnih temperatur, pogostejši vročinski valovi ter povečana tveganja za poplave in suše. Urbana območja so še posebej ranljiva, saj gosta pozidava, omejena vegetacija in neprepustne površine stopnjujejo toplotno obremenitev ter zmanjšujejo odpornost. Ta pojav mestnega toplotnega otoka ima pomembne posledice za zdravje ljudi, infrastrukturo in okolje, zaradi česar so mesta ključne točke prilagoditvenih strategij. Raziskava obravnava dolgoročne podnebne spremembe v Sloveniji s poudarkom na Mariboru, drugem največjem mestu v državi. Geografska lega Maribora v Dravski dolini v kombinaciji s starajočim se prebivalstvom povečuje njegovo ranljivost za ekstremne vročinske dogodke. Ugotovitve kažejo na sezonski premik intenzivnosti mestnega toplotnega otoka iz hladnejših v toplejše mesece ter na znatno povečanje v prihodnjih desetletjih, zlasti na industrijskih območjih. Z združevanjem visokoločljivostnih podnebnih podatkov, satelitskih posnetkov in socio-demografskih kazalnikov raziskava prepoznava prostorske vzorce toplotnega stresa in izpostavlja najbolj ranljiva območja. Rezultati predstavljajo znanstveno podlago za trajnostno urbano načrtovanje in učinkovito prilagajanje na podnebne spremembe.

Univerzitetna založba
Univerze v Mariboru

1 Introduction

Climate change is one of the defining global challenges of the 21st century. Global surface temperatures have already risen by approximately 1.1°C relative to pre-industrial levels, and each additional 0.5°C of warming is expected to further increase the frequency and intensity of hot extremes, heavy precipitation, and droughts. Under high-emission scenarios, global mean temperature could rise by 3.3–5.7°C by the end of the century, leading to severe impacts on ecosystems, health, and economies (Intergovernmental Panel on Climate Change, 2021).

Europe is particularly vulnerable. The European Environment Agency (2025) highlights that climate-related risks such as heatwaves, floods, and droughts will intensify even under optimistic scenarios. These changes will disproportionately affect cities, where dense built forms, impervious surfaces, and limited vegetation amplify thermal stress through the urban heat island (UHI) effect (Oke, Mills, Christen, & Voogt, 2017). The UHI not only exacerbates heat exposure but also increases the incidence of heat-related illnesses and mortality (Grimmond, 2007). The Local Climate Zones (LCZ) classification provides a useful framework to systematically analyse these patterns in urban areas (Stewart & Oke, 2012).

Maribor, Slovenia's second-largest city, offers a critical case study. Its geomorphological setting in the Drava valley, combined with an ageing population, makes it particularly sensitive to heat stress (Horvat, 2015). Recent studies show a seasonal shift of UHI intensity from winter toward spring and summer, with projections suggesting more than a 60% increase in intensity in southern industrial zones by the end of the century (Žiberna, 2021; Žiberna & Ivajnšič, 2022).

This study therefore examines long-term climate change in Slovenia and evaluates heat stress distribution in Maribor by integrating climate datasets, satellite imagery, and socio-demographic indicators. The findings provide evidence for sustainable urban planning and climate adaptation strategies.

2 Research area

The research area encompasses the Municipality of Maribor (Fig. 1), with a particular focus on the urban settlement as its central unit. Maribor is located in the northeastern part of Slovenia, within the Podravska statistical region, along the middle course of the Drava River. As the country's second-largest city, it functions as a regional administrative, economic, and cultural centre.

The city's relief is defined by its position in the Drava valley, situated between the Slovenske gorice hills to the north and the Pohorje Massif to the south. The urban centre lies at an elevation of approximately 270 m, on a river terrace shaped by the Drava River. Land use reflects a high degree of urbanisation. Central zones are predominantly residential and commercial, while industrial complexes, transport corridors, and agricultural land are situated on the periphery. Urban development is characterised by a mixture of a historical centre, modern residential blocks, and suburban areas. Green areas (urban forests and parks) and the forests of Pohorje play an important heat stress mitigation role within the urban system (Pipenbaher et al., 2022).

Figure 1: True colour composite satellite image and the municipality of Maribor
Source: Google. (n.d.), retrieved September 23, 2025, from URL: https://www.google.com/maps/; Eurostat Geodata, from https://ec.europa.eu/eurostat/web/gisco/geodata, 2025.

According to census data (SURS, 2025), Maribor has a population of 114,301 inhabitants. Population growth stagnated in the 1980s and was followed by depopulation in the 1990s and after 2000. Natural growth has been constantly negative from 1985 onwards, and net migration was negative between 1992 and

2007. Maribor is also showing the most unfavourable age structure of the population, with the highest proportion of the elderly population and the highest ageing index (Horvat, 2015).

Maribor's temperate continental climate (Vršič et al., 2014) is characterised by considerable seasonal temperature variability, cold winters, and moderately hot summers. According to data provided by the Slovenian Environmental Agency (ARSO) for the period 1971–2000, average July temperatures reach about 20.1°C, while January averages fall below 0°C. Precipitation is relatively evenly distributed throughout the year.

3 Methodology

3.1 Data sources and acquisition

a) Climate data

High-resolution climatological data were obtained from the CHELSA database version 2.1, specifically CHELSA_bio1 (mean annual air temperature in °C) and CHELSA_bio12 (mean annual precipitation in mm) at ~1 km spatial resolution for historical (1981–2010) and future (2071–2100) periods (Karger et al., 2023). Future climate projections were derived from the MPI-ESM1-2-HR Earth System Model under the SSP585 scenario, representing a high greenhouse gas emission pathway with radiative forcing reaching 8.5 W/m² by 2100.

b) Satellite imagery

Landsat 9 Collection 2 Level-2 surface reflectance and surface temperature data were acquired from the USGS Earth Explorer platform. The selected satellite image captured on July 26, 2024, provided cloud-free coverage during peak summer conditions.

c) Administrative units

In order to spatially limit our climate and satellite data sets, two administrative units databases were used: (a) the European land area units, available on the Eurostat GISCO platform, and (b) the municipal vector layer available on the STAGE data platform owned by the Slovenian Statistical Office. Additionally, population data were downloaded from the STAGE platform on a 100 m vector grid. Population data were later considered as one of the predictor variables for heat stress evaluation.

3.2 Data preprocessing

All spatial datasets underwent standardisation to ensure geometric consistency. Vector boundaries were reprojected to WGS84 (EPSG:4326) for broad-scale analysis, while municipal analysis utilised the UTM Zone 33N projection (EPSG:32633). Raster datasets were clipped to study area boundaries using mask-based extraction procedures.

3.3 Climate change impact assessment

Long-term climate trends were quantified through temporal differencing of bioclimatic variables using raster algebra:

Temperature Change (ΔT) = $T_{2071-2100}$ - $T_{1981-2010}$
Precipitation Change (ΔP) = $P_{2071-2100}$ - $P_{1981-2010}$

Municipal-level statistics for both climate variables were derived through zonal statistics, computing mean values and standard deviations for each administrative unit.

3.4 Urban heat stress modelling

Heat stress assessment for Maribor integrated multiple variables through a composite modelling approach:

a) Land Surface Temperature (LST) was calculated from Landsat 9 thermal infrared band using the USGS Collection 2 algorithm: LST (°C) = ($Band_{10} \times 0.00341802 + 149.0$) - 273.15
b) Vegetation density was assessed using the Normalized Difference Vegetation Index: NDVI = (NIR - Red) / (NIR + Red)

c) Population density was spatially interpolated using Inverse Distance Weighting (IDW) with 500-metre cell resolution. Point centroids were generated for each population grid cell, creating spatially explicit population density estimates.
d) Composite Heat Stress Index: The Fuzzy Raster (large membership) function integrated multiple risk factors. Each input layer (LST, population density, temperature change projections) underwent fuzzy membership transformation, normalising values to a scale from 0 to 1. The composite index was calculated as:

Heat Stress Index = Fuzzy (LST) + Fuzzy (Population) + Fuzzy(ΔT) + NDVI

3.5 Technical implementation

All analyses were conducted using QGIS 3.44.0 (QGIS Development Team, 2024) with processing algorithms including Raster Calculator, Clip Raster by Mask Layer, Zonal Statistics, IDW Interpolation tools and Fuzzy Raster.

4 Results

An analysis of climate projections, Fig. 2 and Fig. 3, for municipalities in Slovenia indicates significant changes in average temperatures and precipitation between 1981–2010 and the projected period 2071–2100. In addition, a case study of the city of Maribor illustrates the spatial distribution of anticipated heat stress.

Fig. 2 shows the change in average temperature, with an increase ranging from +4.07 to +4.65°C. The lowest warming is expected in the Alpine regions of western Slovenia (approx. +4.1°C), where altitude and more frequent cloud cover mitigate temperature rise. The highest warming, up to +4.65°C, is projected for eastern and southeastern lowlands, creating a clear climatic gradient from the coast towards the continental interior. These results demonstrate that warming in Slovenia will not be uniform but will reflect natural climatic heterogeneity.

Alongside the temperature rise, Slovenia is expected to experience a significant decline in average precipitation (Fig. 3), with changes ranging from approximately -143 mm to -66 mm by the end of the century. The largest declines are expected in the Julian Alps and their foothills, which are key sources of water for the national river system. A more moderate but still noticeable decrease is expected in central and southern Slovenia. These changes indicate a higher risk of summer drought and water shortages, and reduced snowfall in mountain regions, with possible consequences for agriculture, water management, and winter tourism. Unlike temperature, changes in precipitation are more spatially fragmented, reflecting the greater sensitivity of precipitation to local topography and atmospheric circulation patterns.

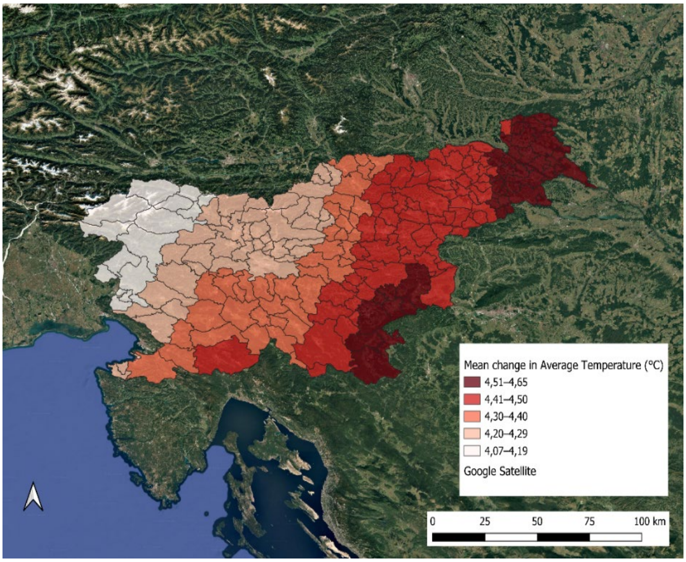

Figure 2: Potential mean change in average air temperature in Slovenian municipalities (2071–2100, 1981–2010)
Source: Authors.

In general, the spatial distribution of heat stress in Maribor, as presented in Fig. 4, shows that the most critical hot spots are located in the city centre and in the southern residential areas, which are strongly affected by the UHI. Meanwhile, the suburban areas and green spaces generally show lower levels of heat stress. In the historic city centre, the cooling potential of the Drava River appears to be limited due to concrete surfaces and dense surrounding development. The analysis, conducted with a spatial resolution of 500 × 500 m, may smoothen local variability, as small features such as parks or stadiums can lower the classification of entire cells despite dense, poorly ventilated, and vegetation-poor surroundings. This highlights the need for more detailed data in future research to better capture the heterogeneity of the urban environment. Overall, the results demonstrate that Maribor will face significant heat stress by the end of the century, with the highest risks clustered in the high-density urban centre, which highlights the urgent need for urban adaptation measures.

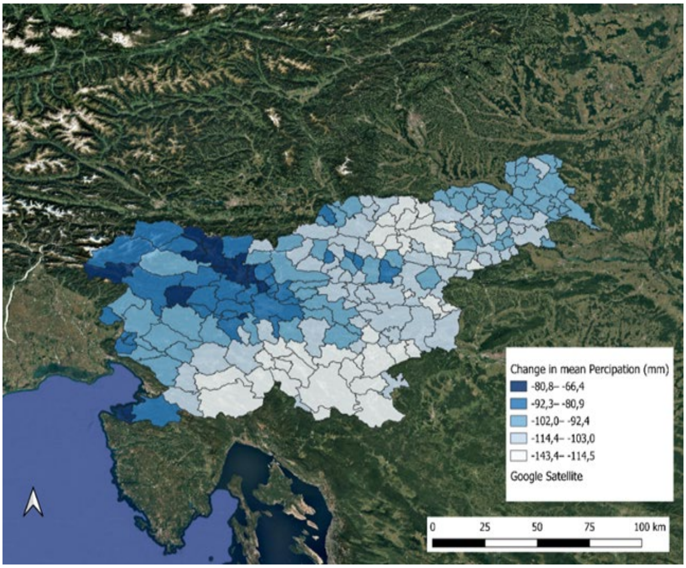

Figure 3: Potential change in mean precipitation in Slovenian municipalities (2071–2100, 1981–2010).

Source: Authors.

Figure 4: Predicted heat stress in Maribor under the MPI-ESM1-2-HR SSP585 scenario, representing a high greenhouse gas emission pathway with radiative forcing reaching 8.5 W/m² by 2100

Source: Authors.

5 Discussion

Our research was heavily dependent on open data sources provided on different scales (global, regional, local). While other articles may focus on either urban morphology or climatic factors (or both), this research relies purely on modelling, predictions based on climatic, land cover and population data. Since UHI research has a rich history, many principles have been defined throughout the years. Indeed, Arnfield (2003) summarised past advances in UHI research based on Oke's generalisations (1982), and concluded that many climatic and non-climatic factors play an important role; therefore, urban heat stress (HS) modelling remains a complex task in modern science.

Heat stress in itself is heavily dependent on population density, as it primarily reflects conditions affecting residential areas rather than the physical spaces that are, or may be, more directly impacted by the urban heat island (UHI) effect (for example, industrial areas). We could also explain HS as a modified metric of UHI, essentially for the quality of human life. Urban morphology, population density, and patterns of residential spaces cannot be predicted, as they rely on planning policies which could change drastically in the future. Measures like NDVI (which are essential in UHI modelling) are also difficult to predict for similar reasons; however, creating predictions like in this research is inevitable to have a ground idea of what the urban climate might look like if no serious changes take place. This study aims to prompt discussion between planners and public policy makers to address these threats against liveable residential areas and to also enhance further investigations in urban climates in Slovenia.

Our research could be improved through collecting more precise local data, validating the demographic situations in the city, implementing more predictor variables, like NDBI (Normalized Difference Built-Up Index) values or comparing the LST values found on urban spaces with the ones measured in rural areas. Researching morphological patterns as a separate topic would make more precise predictions in HS. UHI could also be described as a result of other urban climatic anomalies, such as air flow (Borrego et al., 2006) or precipitation (McLeod et al., 2024). As we examine the interrelated climatic mechanisms, it becomes clear that the city's structure, in a way, shapes its own climatic deviations from the local climate.

Another way to inspect HS is from a health perspective. Studies found a correlation between heat-related health problems and UHI. Long-term HS enhances the effect of heat waves on humans (Tan et al., 2008). These ideas propose not only problems related to living comfort, but also to serious health concern, which further strengthens the sincerity of urban climate research.

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