

Temporal variations of urban cold island formation in cold cities

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Keywords: Urban Cold Island, Urban Morphology, Remote Sensing, Landsat, Erzurum

Abstract: Climate change is a global phenomenon whose effects are increasing. Climate change triggers extreme conditions, and these extreme conditions occur as rapid warming and/or cooling. Like rapid warming, cooling down affects the physiological structure of the human being. This study was carried out in Erzurum, one of the coldest cities in Turkey. In the study, the Landsat data band was analyzed with the support of remote sensing. The results of the analysis were confirmed by field study data. UCI formations were observed during the cold months between the years 2014 and 2022. According to observations, UCIs showed an irregular change. The highest UCI formation occurred in 2017 with a size of 6.08 km², and that year in the study area, the surface temperatures of minimum -42.1°C, maximum -24.1°C, and average -35.6°C were measured. In 2018, the lowest UCI formation was determined, with a size of 0.155 km² over an 8-year period. In the cold month of 2018, the surface temperature was measured at a minimum of -19.8°C, a maximum of -5.8°C, and an average of -10.5°C. The study determined that UCI formations in the winter are inevitable in the Erzurum city center, and these formations vary depending on the temperature. The aim of this study is, first, to reveal the temporal changes of UCI formations in the cold city of Erzurum; second, to determine the effect of urban morphology on these changes; and third, to discuss possible solutions.

1. Introduction

In the 19th century, the rapid advancement of technology led to an increase in the population. The world population has shown a rapid increase in the last century. The rise in population and the advancement of technology have triggered migration from rural areas to cities. The urban population worldwide has increased approximately 4.6 times in the last 70 years and is expected to reach 6.4 billion by 2050, which corresponds to 68% of the world population (Huang et al., 2021). The globalization of society has led to the

intensification of urban structures and the formation of different microclimate areas within cities. As a result, significantly different climatic conditions within cities affect people's health (Chen et al., 2017; Scovronick et al., 2018; Urban & Kysely, 2018). The physical activities of individuals whose health is affected are also restricted (Koç et al., 2022; Yılmaz et al., 2016; Yılmaz et al., 2018). Additionally, climate impacts housing, clothing, and eating habits (Toy et al., 2007; Yılmaz et al., 2016; Yılmaz et al., 2018). One of the important factors influencing different climate types in the city is land use type and open green areas. The high thermal mass emitted by concrete and asphalt roads contributes to the increase in ambient temperature caused by urban climate change. This includes the low ventilation capacity of urban canyons formed by high-rise buildings and the heat emitted from vehicles (Akbari et al., 2016). The ambient temperature in the city does not show a uniform increase at every point. In some areas within the city, the temperature distribution is numerically higher, and these areas are referred to as urban heat islands (UHI) (Santamouris, 2018). Within an urban UHI, there are scattered areas with cold spots that are significantly cooler than the surrounding environment, a phenomenon known as an urban cold island (UCI) (Park et al., 2019). There are studies on UCIs in the literature (Pórolniczak et al., 2017; Tian et al., 2023). Extreme cold waves have become more noticeable in recent years due to climate change (Mayhorn and McLaughlin, 2014; Wang et al., 2017). It is evident that cold areas indirectly affect human health (Butler, 2012; Daily and Ehrlich, 1996). An extremely cold environment can cause rapid heat loss from the human body, lowering skin and body temperature, which can lead to decreased muscle performance, reduced grip frequency and grip strength, impaired hand and finger dexterity, decreased maximum voluntary contraction, and diminished physical work performance (Wu et al., 2022). Exposure to a cold environment can pose human health risks, including cold-related symptoms, diseases, and injuries (Zlatař et al., 2019). These climatic effects on humans lead to a need for climate adaptation. Adaptation between humans and climate is managed through various plans, and developing technologies facilitate this adaptation planning. In fact, there are many recent studies on the use of remote sensing in climate planning (Ahmed, 2018; Gintamo et al., 2021; Koç et al., 2022; Peeters, 2016; Wang et al., 2018; Wicki, 2018; Zheng et al., 2018). These studies generally focus on urban heat islands (Koç et al., 2022; Luan et al., 2020; Shirani-Bidabadi et al., 2019; Wang et al., 2019; Zhou et al., 2018) and urban thermal comfort maps (Goldblatt et al., 2021; Sharma et al., 2021).

Turkey is located between the temperate and subtropical zones (Sensoy et al., 2008). The fact that Turkey is surrounded by seas on three sides, combined with its extensive mountain ranges and diverse landforms, has led to the emergence of various climate types (Sensoy et al., 2008). In the coastal regions of Turkey, more temperate climate characteristics are observed due to the influence of the seas. In contrast, the inland regions experience a continental climate because the North Anatolian Mountains and the Taurus Mountain Range prevent sea moisture and air flow from reaching these areas. In the continental climate, winters are quite cold and long, while summers are cool. In low-altitude regions, however, temperatures are high in the summer. During the cold season, the region is often covered in snow, and frost is common.

Erzurum, which is the primary focus of this study, experiences one of the most extreme climates in Turkey, known as the harsh continental climate, due to its altitude. Physical (mechanical) weathering is high because of the significant temperature differences. The wettest season in Erzurum is late spring and early summer, with most precipitation occurring as convectional rainfall. The driest season is winter, with snowfall occurring approximately 150 days a year (TKTB 2020). The precipitation regime is not regular. Vegetation is generally composed of mountain meadows and coniferous forests. Forests and heaths make up 9% of the area, while meadows and pastures make up 68%. The average summer temperature in Erzurum is 18.4 °C. It is one of the provinces with

the lowest average summer temperature. It is one of the coldest provinces in Turkey, with an average January temperature of -7°C (TKTB 2020).

The aim of this study is to map the temporal and spatial changes of UCIs caused by changes in the built environment and land use in Erzurum city center, one of the coldest cities in Turkey, and to discuss possible solutions.

2. Materials and Methods

2.1 Study Area

The study area is the city center of Erzurum, which is one of the 81 provinces of Turkey. Erzurum is located between 39 North and 41 East longitudes (Figure 1). Erzurum generally shows high and plateau characteristics. It is a province surrounded by Palandöken Mountain in the south and Kargapazarı Mountain in the north. Erzurum is one of the provinces with the highest altitude (1900 m.) in Turkey. At the same time, the city of Erzurum is one of the coldest cities in Turkey. The annual average temperature was 5.7°C , and in the coldest month, January, it was recorded at -9.1°C . According to the 2021 population data for Erzurum city center, the population is 348,156. (TÜİK, 2021). The study area boundary in Erzurum city center consists of an area of 38.4 km² (Figure 1).

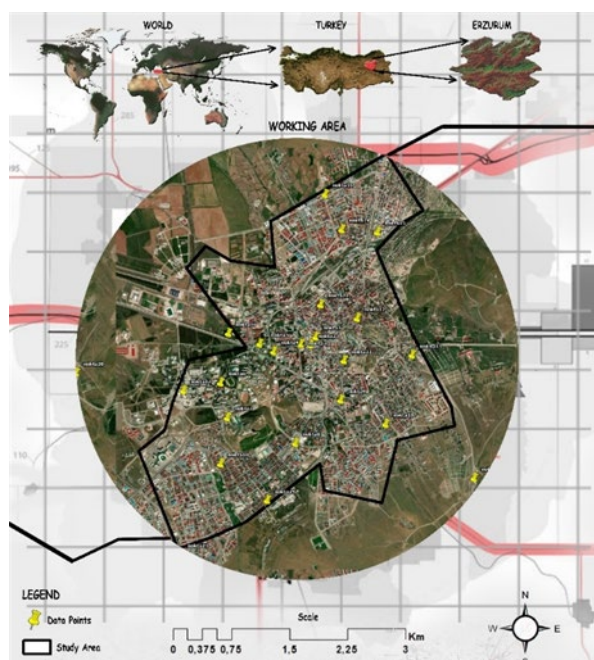


Figure 1. Location of the study area

The average elevation of Erzurum city center is around 1900m (Figure 2). Erzurum has been a settlement since the first periods of history. The city is also known for its historical monuments and winter sports facilities. In Erzurum, which is the fourth largest province of Turkey in terms of surface area, the main source of income is agriculture and animal husbandry, and the city has come to the fore with winter tourism in recent years.

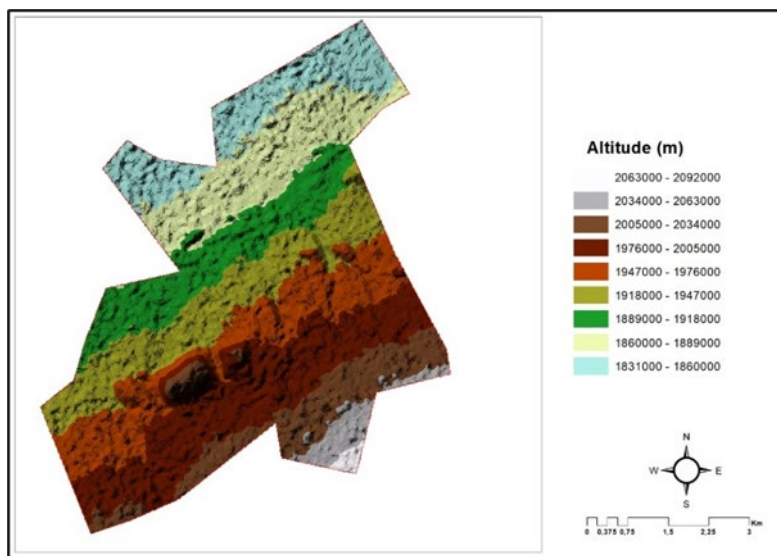


Figure 2. Topographic map of the study area

2.2 LST Analyzes of The Study Area

The surface temperature mobility of the research area was determined using data obtained from the Landsat 8 satellite. Landsat 8 operates functionally in the visible, near-infrared, short-wave infrared, and thermal infrared ranges. The satellite has the ability to capture 400 photographs on a daily basis. The TIRS sensor, developed by NASA Goddard Flight Center, is a thermal imaging sensor specifically designed for emergency applications, such as measuring evapotranspiration rates to aid with water regulation. The TIRS data was captured in alignment with the OLI data in order to produce 12-bit Landsat 8 data that has been corrected for radiometric, geometric, and terrain factors. Similar to the OLI, this sensor is constructed as a pushbroom sensor with a cross-track field of view of 185 kilometers. The Thermal Infrared Sensor (TIRS) acquires data using two extended wavelengths. However, only the 10th band will be compatible for the continuing of data using the previous Landsat satellites. The investigation utilized Band 10, which has a wavelength range of 10.30–11.30 μm with a spatial resolution of 100m.

This study utilized surface temperature (LST) data acquired from the Landsat 8 satellite to assess urban surface temperature and cold islands. Figure 3 depicts a chart that is utilized for the conversion of digital data from bands 5, 4, and 10 of the Landsat satellite into spectral light.

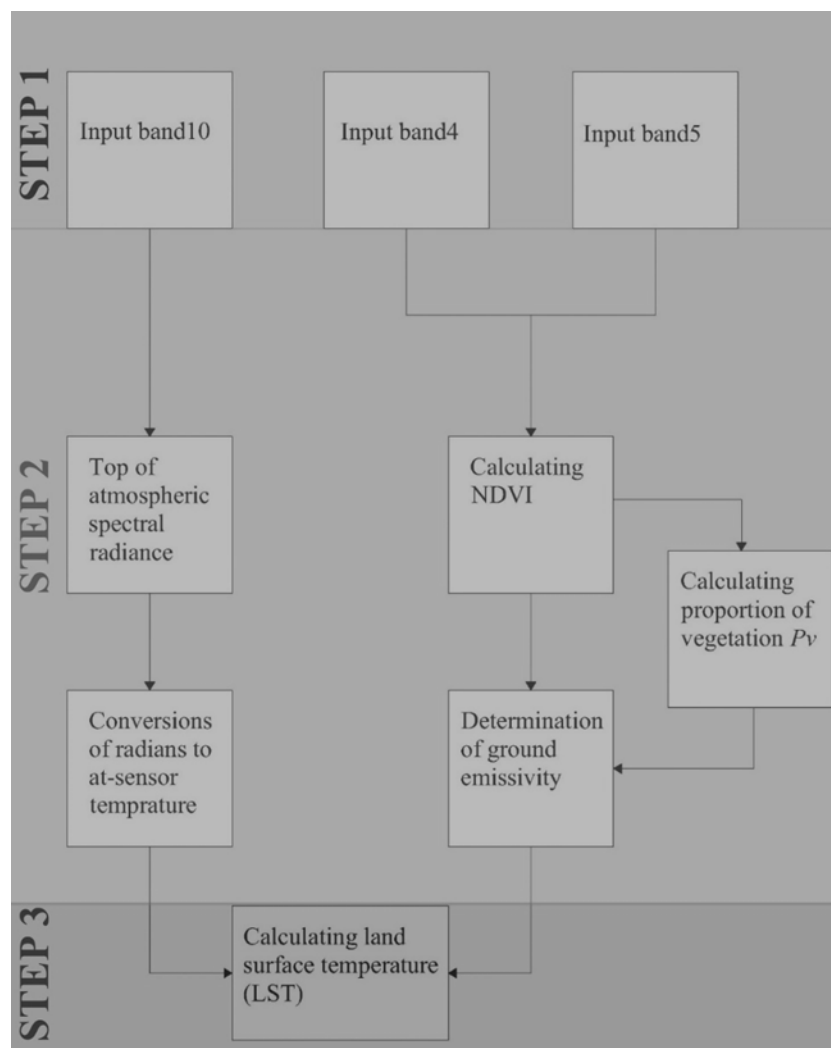


Figure 3. Flowchart showing the stages of creating LST maps of the study area

An analysis was conducted on the band data of the Landsat 8 satellite, using the Arc GIS 10.8 program (Chander and Groeneveld, 2009; Jimenez-Munoz et al., 2014; Koç et al., 2022; Rozenstein et al., 2014; Turk et al., 2021). During the initial phase of the investigation, the satellite images from Landsat 8 were categorized based on several bands. The atmospheric radiation value in this stage was determined using the following equation.

$$L\lambda = \text{Band10} \times 0,003342 + 0,1 \quad (1)$$

$L\lambda$ = Spectral luminance at sensor aperture (W / (m² sr μm))

In the second step, another equation was used to convert the atmospheric irradiance value to the sensor temperature (Chander and Markham, 2003).

$$TB = (1321,08 / \ln((774,89 / (L\lambda)) + 1)) - 273,15 \quad (2)$$

Also, the following equation was used to obtain NDVI maps (Hatfield et al., 1985; Liu and Zhang, 2011; McFeeters, 1996; Zhang et al., 2006). Normalized plant density index maps are important because they show differences in temperature fluctuations on the natural surface according to plant densities (Irish, 1998; Landsat; Zanter, 2016).

$$NDVI = \text{Flood}(\text{Band5} - \text{Band4}) / \text{Flood}(\text{Band5} + \text{Band4}) \quad (3)$$

NDVI= Normalized plant density index maps

In the other part of the study, the calculation of the vegetation ratio was made. The following equation was used to calculate the vegetation ratio (Landsat; Zanter, 2016).

$$Pv=0,004 \times (NDVI) + 0,986 \quad (4)$$

Pv=Calculation of vegetation ratio

In the last stage of the study, maps of surface temperature (LST) were created with a minimum margin of error.

$$LST = TB / (1 + (0,00115 \times TB / 1,4388) \times \ln(Pv)) \quad (5)$$

2.3 In Situ Analysis and Creation Of Geostatistical Distribution Maps

The General Directorate of State Meteorology Stations dataset indicates that the coldest dates in the study area fall between January 17 and February 7. The research team obtained surface temperature, air temperature, air humidity, and wind speed data between 13:00 and 14:30 from 24 different predetermined points within and outside the study limits, taking into account the sky clarity (Figure 4).

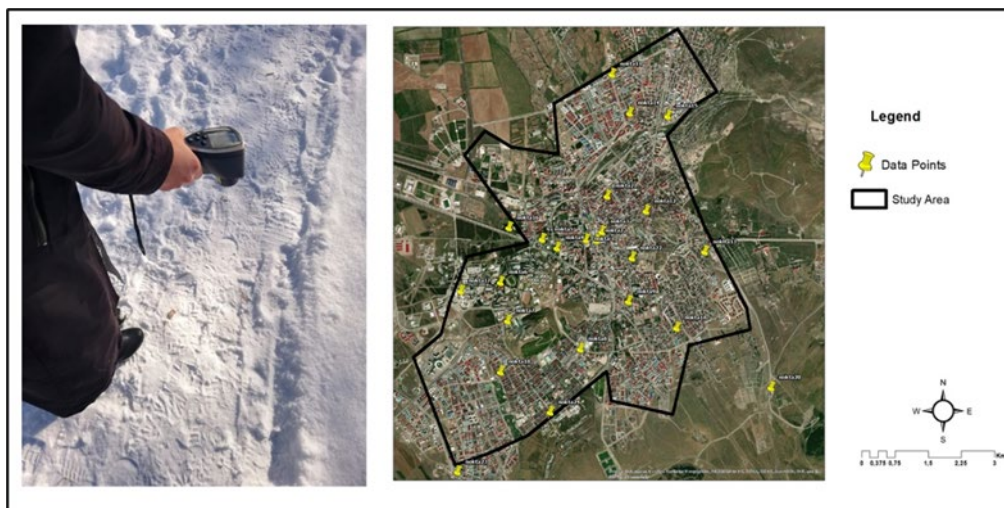


Figure 4. Locations where point data of the study area is taken

According to the obtained point data, spatial raster maps were created with the Kriging method in the Geostatistical Analyst module of ArcGIS 10.8 software (Childs, 2004; ESRI, 2020; Johnson et al., 2018). The following equation was used in the Kriging method to create raster maps (Childs, 2004; ESRI, 2020; Johnston, 2004; Johnston et al., 2001; Koç et al., 2016; Xiao et al., 2016).

$$Zp = \sum_{i=1}^n Wi Zi \quad (6)$$

Zp: Expected fluctuation value of point P

Wi: corresponding weight value for each Zi value

Zi: The fluctuation value of the points used

n: Number of points used

3. Results

The research area's urban cold islands were identified using surface temperature (LST) assessments conducted with the Landsat 8 satellite. Therefore, after considering the orbital times of the satellite and the meteorological data, the thermal studies conducted in January (Figure 5) revealed the presence of urban cold island formations

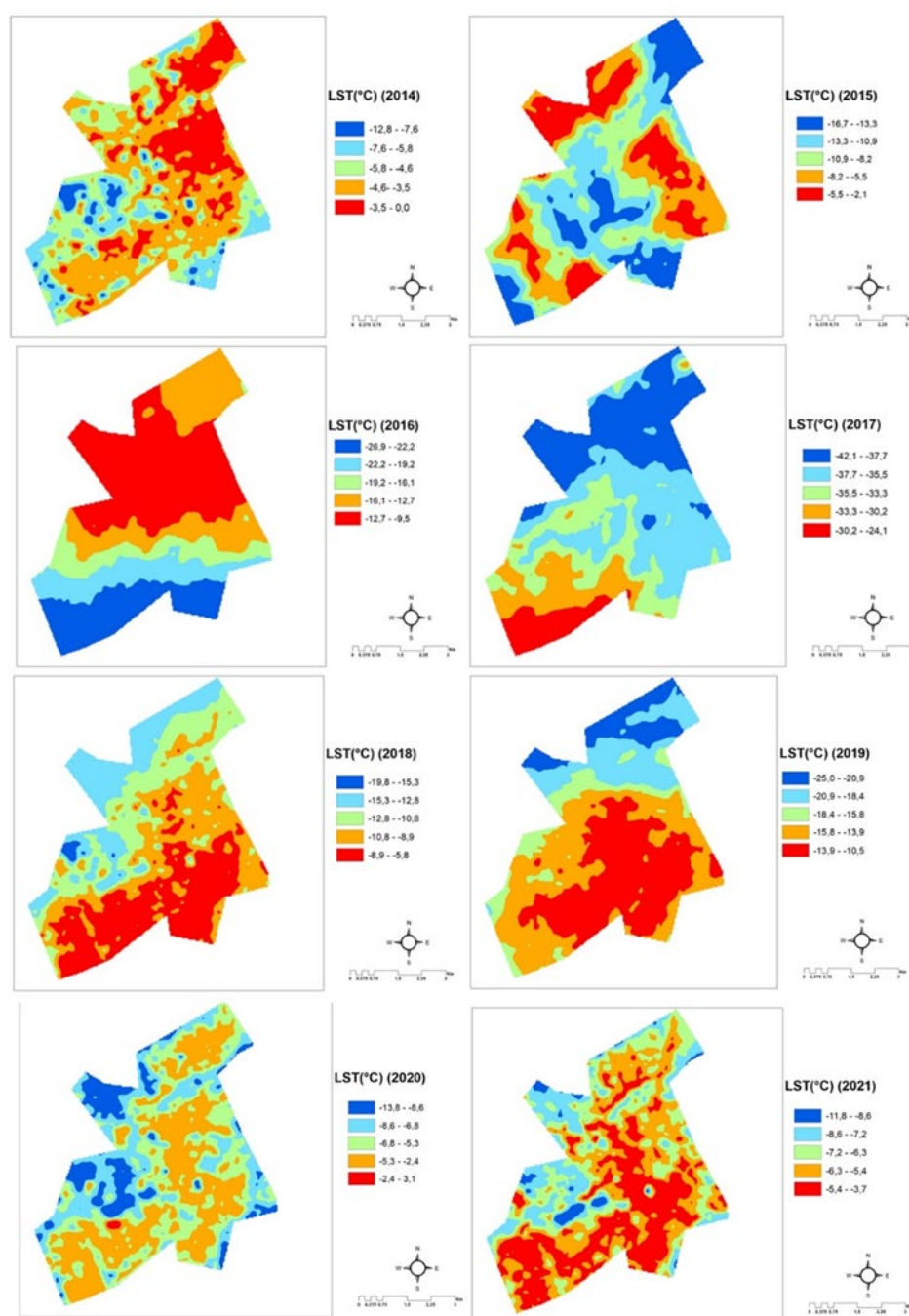


Figure 5. LST maps of the study area

The LST analyses conducted in 2014 revealed that the lowest recorded surface temperature within the research area was -12.8°C , the highest was 0.08°C , and the average temperature was -4.6°C . Based on the existing data, a UCI was detected in the same year. From the data collected, it was concluded that the UCI area covers 0.64 square kilometers. Conversely, the total area of hot and somewhat pleasant regions was calculated to be 4.82 square kilometers (Figure 5).

During the examination based on the LST measurements obtained in the winter of 2015, UCI formations were also detected. The observations revealed a minimum surface temperature of -16.7°C , a maximum of -2.1°C , and an average of -9.4°C . Based on the thermal data, the study region showed the presence of 3.83 km² of UCI formation and 4.82 km² of substantially warmer, comfortable surface temperature (Figure 5).

The 2016 LST examination of the study region recorded a minimum surface temperature of -26.9°C , a maximum of -9.5°C , and an average of -15.7°C . Indeed, these data indicate that UCI formations were detected once again throughout the same era, in accordance with the urban morphology. The total area of UCI that has been established is 3.73 square kilometers, whereas the area that is relatively pleasant is 8.61 square kilometers (Figure 5).

Based on the 2017 LST investigation, the UCI areas were found to be 6.08 km², while the moderately pleasant areas were judged to be 1.63 km². The minimum surface temperature recorded during this period is -42.1°C , while the maximum temperature is -24.1°C . The average temperature for this period is -35.6°C , as shown in Figure 5.

The 2018 LST analyses recorded a lowest surface temperature of -19.8°C , a maximum of -5.8°C , and an average of -10.5°C . According to this data and consistent with the structure of the city, UCI forms were noticed once again throughout the same time period. The extent of UCI formation has been measured to be 0.15 square kilometers, whereas the comparatively more comfortable region spans 6.67 square kilometers (Figure 5).

UCI forms were also detected during the assessment conducted based on the LST values obtained during the winter season of 2019. The observations revealed a lowest surface temperature of -25.0°C , a maximum of -10.5°C , and an average of -15.8°C . The study region revealed the presence of 2.02 square kilometers of UCI formation and 7.70 square kilometers of substantially warmer, comfortable surface temperature, as indicated by the thermal data (Figure 5).

Based on the LST analyses conducted in 2020, the research region recorded a minimum surface temperature of -13.8°C , a maximum of 3.1°C , and an average of -6.3°C . Based on the area data, a UCI was detected during the same year. From the above observations, it was concluded that the UCI region measures 2.54 km². Conversely, the area that is hot and slightly more pleasant was found to be 0.05 km² (Figure 5).

Along the same line, UCI formations were observed in the 2021 LST analyses. The minimum surface temperature measured this year is -11.8°C , the maximum is -3.7°C , and the average is -6.1°C . At the same time, UCI formations were found during this time period. Thus, the amount of UCI formed was determined as 0.508 km², and the hot surface above the average was determined as 6.54 km² (Figure 5).

UCI formations are also observed in 2022 on the maps obtained from on-site measurements. As a matter of fact, during this time, the coldest points were calculated at 1.79 km², while the warmest areas were calculated at 0.98 km² (Figure 6).

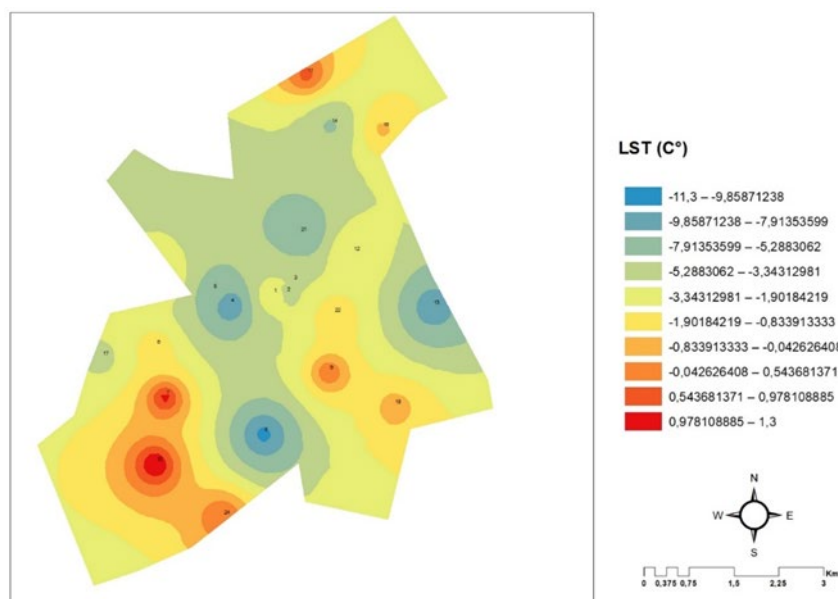


Figure 6. Surface temperature map obtained from on-site measurements

Measurements of air temperature, relative humidity, and wind speed were also conducted in the field during the study, as shown in Figure 7, Figure 8, and Figure 9. The air temperature map displayed disparate temperatures across different areas of the city. Hot air movement was seen in the city center and its vicinity, while low air temperature movement was noted, particularly in areas with wide wind corridors and along the main traffic axis of the city. Indeed, there is an observed disparity of about 8.2 °C in daytime temperatures between the city center and locations that are exposed to open wind corridors (Figure 7).

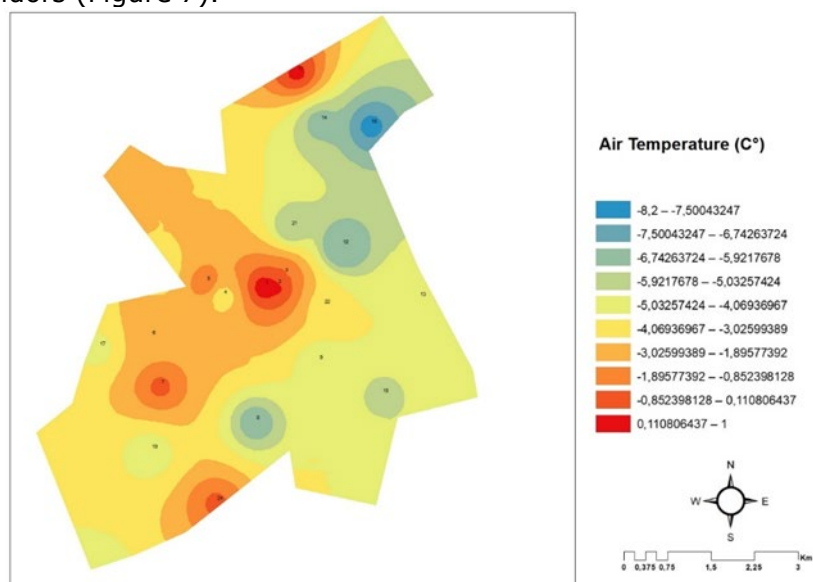


Figure 7. Air temperature map obtained as a result of field studies

Based on the wind distribution map generated in the study area, the data collected during the cold season indicates that there is an average presence of breezes ranging from 0–1.5 m/s. The locations with the lowest wind speed were identified to be in the vicinity of the city center (Figure 8). Similarly, it has been noted that areas with low wind speeds tend to have greater daytime air temperatures.

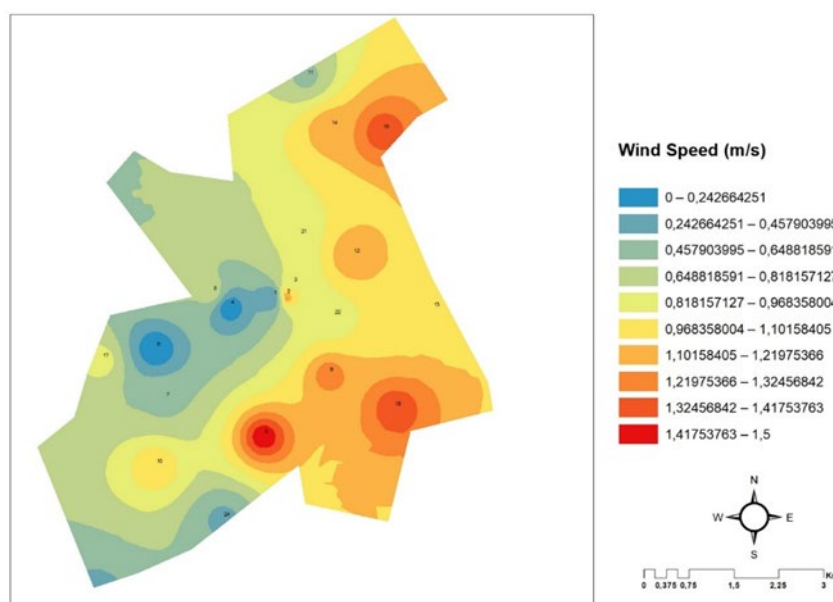


Figure 8. Wind speed map of the study area

The relative humidity chart exhibits variations ranging from 21.5% to 41.5%. Figure 9 shows that the points with the highest relative humidity are the sites that are far from the city center and the outlying points of the center. Indeed, while the air temperature is low in these areas, earlier maps have shown that there are certain locations where the wind speed is slightly elevated.

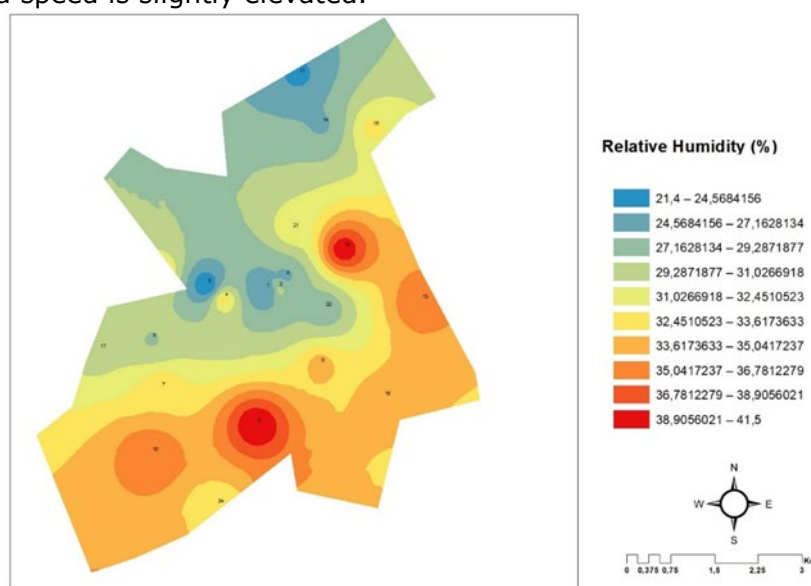


Figure 9. Relative humidity map of the study area

4. Discussion

4.1. Effects of Urban Morphology on UCI

In terms of physicality, air flows occur in the direction from areas of higher temperature to areas of lower temperature. Cool air falls and converges with warm air, while warm air ascends and converges with the cold zone. In metropolitan settings, the cold air that gathers in low-lying regions is drawn towards warmer locations, however certain points in the city maintain constant cold air due to the influence of terrain and vegetation barriers. According to Morakinyo and Lam (2016), vegetative barriers have a cooling effect on the surrounding surroundings. These frigid regions experience a temperature that is 2–4 °C lower than other locations in the city. Humans can get heat stress due to hot climate factors as well as cold stress because of cold climate factors.

One of the factors affecting cold stress is UCIs. The heat generated as a result of anthropogenic effects and the heating of the surface is balanced with the current weather conditions (Huang and Wang, 2019). Urban morphology can divide this heat balance and trigger the formation of urban hot or cold areas. The city of Erzurum is one of the provinces that gets extremely cold during the winter months because of its altitude and location. Sometimes this cooling is so severe that the temperature difference between day and night rises to almost 30 °C. Unfortunately, this temperature difference has a negative impact on human comfort, urban biomes, and the physical infrastructure of the city. Thus, when the results of the analysis of the city of Erzurum are considered on the basis of a holistic approach, according to 10 years of data, UCI formations were observed in the city center (Figure 10). Previous studies in the literature show that although urban centers are warmer than rural areas (Heinl et al., 2015; Jia and Zhao, 2020; Koc et al., 2019; Mahato and Pal, 2019), urban areas can sometimes differ in cooling compared to rural areas. Although UCI formations are generally seen in the outer periphery of the center in the city of Erzurum, according to the long-term average, UCI formations have also been observed in the inner parts of the city, and, accordingly, the inner parts of the city are potentially built environments (Figure 10). UCI formations in urban centers depend on urban morphology. UCI formations are inevitable in locations that are below the average height in cities and do not have wind corridors in terms of topography. Because of the cooling air density, it descends and settles in the collapse (Connolly et al., 2021). If the descending air does not have any mobility, it triggers the formation of islets with a dynamic cooling effect in the city (Chow et al., 2013; Zardi and Whiteman, 2013). The resulting UCIs prevent people's physical movements. Thus, there are examples in the literature of the negative effects of cold air on human health in terms of health (Karthick et al., 2022; Marno et al., 2006; Mercer, 2003; Vasconcelos et al., 2013; Weinhhammer et al., 2021).

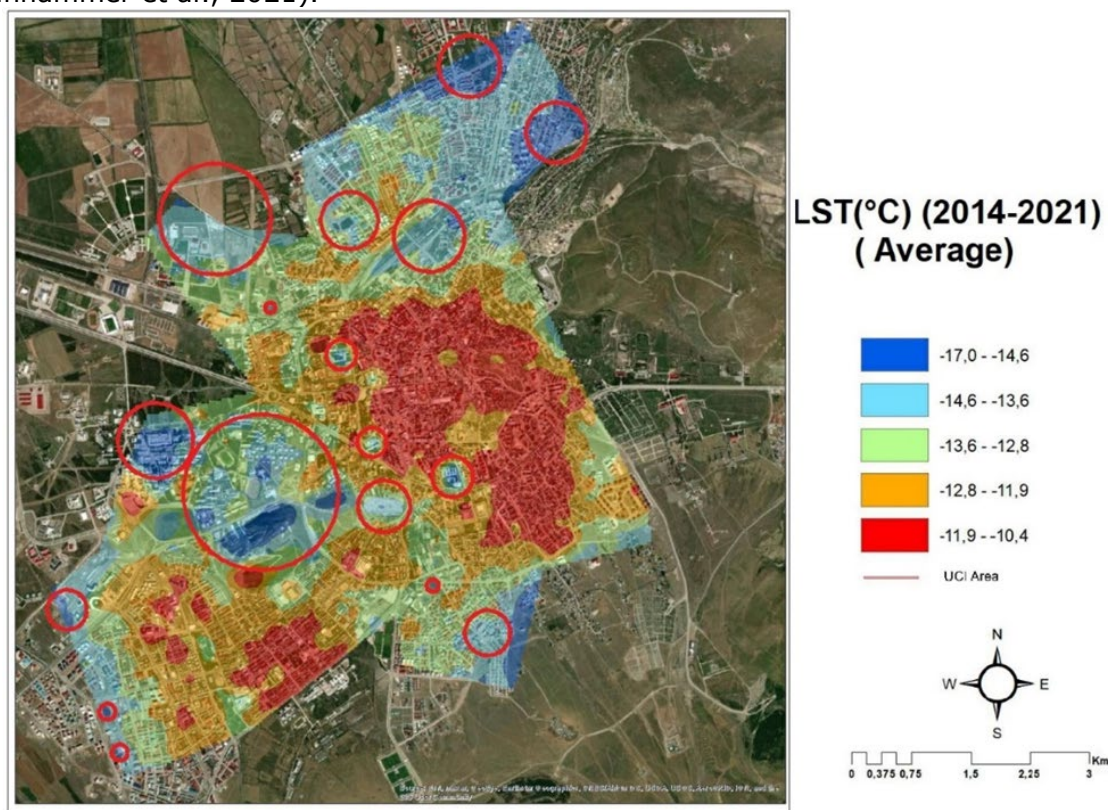


Figure 10. Erzurum City Center LST average for many years

4.2. Temporal Variations of UCIs

Since most of the land surfaces are occupied by impermeable surfaces in highly urbanized areas, rapid heating and cooling occur in urban areas. UCI formations were observed in Erzurum city center according to Landsat 8 and on-site measurement data. As a result of these observations, although it was high in some years, in some years there was almost no UCI formation (Table 1).

Table 1. Data of the study area

Year	Minimum (°C)	Maximum (°C)	Average (°C)	UCI (Km ²)	Heat Area (Km ²)
2014	-12,8	0,08	-4,6	0,64	4,82
2015	-16,7	-2,1	-9,4	3,83	4,28
2016	-26,9	-9,5	-15,7	3,73	8,61
2017	-42,1	-24,1	-35,6	6,08	1,63
2018	-19,8	-5,8	-10,5	0,155	6,67
2019	-25	-10,5	-15,8	2,02	7,7
2020	-13,8	3,1	-6,3	2,54	0,055
2021	-11,8	-3,7	-6,1	0,508	6,54
2022 (on-site measurement)	-11,3	1,3	-3,2	1,79	0,55

The utilization of the Landsat 8 satellite commenced in 2013. Data sets were generated in January 2014 as a result of the meteorological conditions of the study area. To validate the precision of the generated datasets, the 2022 data were acquired using on-site measurements, and themed maps were then generated using this data. Consistency is evident between the Landsat data and the on-site measurement maps. UCI structures have an area of 2.43 km² based on Landsat data, however on the thematic 2022 map generated with on-site measurements, they are measured to be 1.79 km². UCI formations were predominantly observed in 2017 and somewhat in 2018. Fluctuations in UCI occurrences are sporadically detected from 2014 to 2022 (Figure 11). Table 1 demonstrates that the most significant detrimental impact in UCI formations occurs during the time period with the lowest minimum temperature.

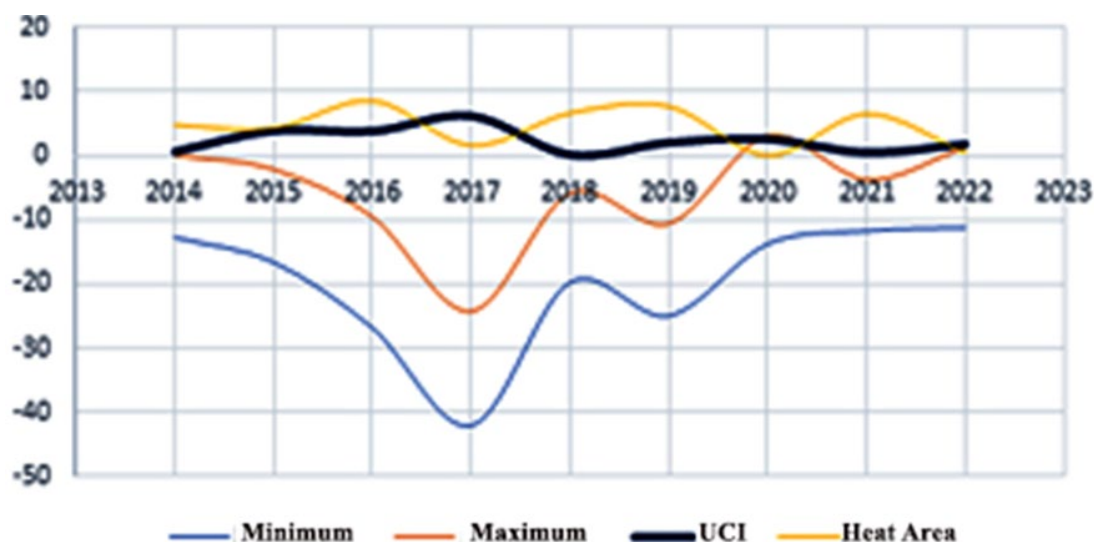


Figure 11. Change of UCIs over the years

4.3. Study Area and Satellite Selection

Location selection is a crucial criterion in UCI studies. Because UCI studies have been conducted in cities with cool and cold climates, such as Ponzan (Pórolniczak et al., 2017) and Bragança (Gonçalves et al., 2018), Although there are many urban heat island studies in the literature (Bornstein, 1968; Dewan et al., 2021; Kim, 1992; Kim and Brown, 2021; Montávez et al., 2000; Oke, 1973; Stewart, 2011), UCI studies very few. Erzurum city was chosen as the area in the UCI study because Erzurum is one of the important cities of Turkey, which characterizes the general characteristics of cities with a cold climate. In the city center, there is a temperature difference of 40°C, especially in winter. While running at -30°C at night, it can reach +10°C during the day. The large temperature difference causes physical overshoots without freezing or thawing, as well as a decrease in the physiological equivalent temperature of living things. Although UCI studies in the literature are generally obtained with quantitative and on-site observations (Gonçalves et al., 2018; Pórolniczak et al., 2017), we obtained results by using Landsat 8 satellite data and on-site measurements to confirm the data.

5. Conclusions

Urban morphologies have an inevitable impact on Urban Climate Islands (UCIs). The impact of this varies depending on the morphology of the city. The UCI is a regular occurrence in the city center of Erzurum, typically taking place on the coldest days of the year. These events may happen during the day, but their impact is heightened during nighttime. The impact of urban heat island (UCI) phenomenon is growing in Erzurum, particularly in areas with little or no green areas. Simultaneously, wind corridors play a significant role in influencing UCI forms. Based on long-term climate data, the predominant wind direction in Erzurum is from the southwest and northeast. Therefore, the dominant wind direction can vary based on some exceptional weather circumstances. In winter, the north-west wind transports the cold air mass from the mountains to the city center, which speeds up the creation and impact of UCI. Hence, conducting studies in collaboration with local governments, non-governmental organizations, and other relevant entities helps mitigate the impacts of UCI. The construction of green infrastructure alongside wind corridors has a particularly significant impact on improving the urban climate. Green infrastructures are crucial resources that can be utilized to reduce the formation of urban heat islands (UCIs) by offering cool air during the summer and milder air during the winter.

Funding: There is no funding of sources used in this article..

Author contributions: All authors had equal contributions.

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