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Article

Assessment of Winter Urban Heat Island in Ljubljana, Slovenia

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Abstract: Although the urban heat island (UHI) phenomenon is more commonly studied in summer, its influence is also important in winter. In this study, the authors focused on the winter UHI in Ljubljana (Slovenia) and its impact on the urban population, as well as in comparison with a UHI study from 2000. Through a combination of mobile and stationary temperature measurements in different parts of the city, the winter intensity of the UHI in Ljubljana was studied in a dense spatial network of measurements. It was found that the intensity of the winter UHI in Ljubljana decreases as winters become warmer and less snowy. The results showed that the winter UHI in Ljubljana intensifies during the night and reaches the greatest intensity at sunrise. During the winter radiation type of weather, the warmest part of Ljubljana reaches an intensity of 3.5 °C in the evening. In total, 22% of the urban area is in the evening UHI intensity range of 2–4 °C, and 65% of the urban population lives in this range. In the morning, the UHI in Ljubljana has a maximum intensity of 5 °C. The area of >4 °C UHI intensity covers 7% of the urban area, and 28% of the total urban population lives in this area. Higher temperatures in urban centers in winter lead to a longer growing season, fewer snow cover days, lower energy consumption and cold stress, and lower mortality from cold-related diseases compared to the colder periphery.

Keywords: climate change; exposure to urban climate; mobile measurements; stationary measurements; UHI; urban climate

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Citation: Ogrin, M.; Svetlin, D.; Stefanovski, S.; Lampič, B. Assessment of Winter Urban Heat Island in Ljubljana, Slovenia. *Meteorology* **2023**, *2*, 222–238. https://doi.org/10.3390/meteorology2020014

Academic Editors: Andreas Matzarakis and Paul D. Williams

Received: 12 November 2022
Revised: 25 January 2023
Accepted: 19 April 2023
Published: 9 May 2023

1. Introduction

The rapid growth of cities in the 20th century has transformed cities into vast, densely built-up areas with extensive land cover changes. The growth of urban populations also means an increasing impact of the urban environment on the living conditions of the world's population. In 2000, about 47% of the world's population lived in urban areas [1], and in 2020 the share of urban population reached 56% of the world's population. In Slovenia the share of urban population is only one percent below the world average [2]. By 2030, the global share of urban population is expected to increase to 60%, and by that time 44% of the world's population will live in cities with at least half a million inhabitants [1]. However, the effects of the urban environment, e.g., polluted air, noise, etc., reach not only the urban population but also its visitors, which increases their impact on the population. Thus, one can conclude that the majority of the world's population is affected by UHIs and the impact is increasing. Due to their structure, cities represent anthropogenic environments that significantly alter the energy balance between the surface and the atmosphere compared to natural or semi-natural environments, resulting in the formation of an urban climate that is different from the climate of a natural environment (e.g., countryside, natural landscape). The UHI phenomenon has been known for more than a century. Howard was the first to write about this phenomenon [3], and later the phenomenon was studied in many parts of the world, e.g., [3–7]. The influence of a city on its own climate depends on several factors. This influence is due to the fact that in radiative weather conditions, the air near the surface is mainly heated and cooled by the surface, which means that by changing the surface structure (e.g., land use), we also influence the changing mechanism of heating and cooling of the surface. The main processes affecting the formation of UHI are as follows [3]:

- Greater absorption of solar radiation due to repeated reflection from buildings and a larger area receiving radiation (building walls);
- Lower sky view factor that prevents effective night-time cooling of the urban surface. Tall buildings result in a less visible sky, which hinders effective longwave radiation from the surface to the sky;
- Greater absorption of radiation and delayed emission due to buildings and paved urban surfaces;
- A greater proportion of absorbed heat is used for conversion to sensible heat and less for latent heat. This is due to fewer water surfaces and greater dryness of the urban surface;
- Release of heat by human activities: industry, transport, heating, etc., to some extent, human metabolism can also contribute.

The geographic location of the city and time of the year also play an important role. The UHI is most pronounced in radiative weather conditions, and the windier the area and the more changeable, rainy, or cloudy the weather, the smaller the impact of the city on the urban climate [8,9]. UHI intensity varies with latitude. In cities at higher latitudes (polar and subpolar areas) the UHI is most pronounced in the winter months, while in sub-Mediterranean cities it is most pronounced in the summer months. At temperate latitudes, the dependence of the UHI on season does not lead to a consistent result. Some studies [10–14] indicate greater intensity in summer or autumn, while other [15–17] indicate that in the continental part of Europe, especially in the Pannonian Plain and its surroundings, the UHI is usually most pronounced in winter. Studies from the USA also confirm a greater UHI in summer. In New York City, summer and autumn UHI intensity reached 4 °C, compared to winter and spring values of 3 °C [8]. Additionally, in cities in the continental USA the average amplitude of the UHI (land surface temperature) is smaller in winter than in summer by 3 °C [18].

The UHI in Ljubljana has been discussed several times. Gams and Krevs [19] studied the climatological differences of some cities and their periphery in Slovenia and Austria, including Ljubljana and Maribor, where they found the most striking UHI phenomenon with UHI intensity at average temperatures of 1 and 0.9 °C based on temperature data from the inner city and its periphery. The first comprehensive study of the UHI in Ljubljana was conducted in 2000 [6]. It was found that the UHI in Ljubljana is less pronounced on average in winter, but that the greatest differences in individual cases can also be found in winter, which is due to the snow cover. Later, some more studies were carried out. Ogrin and Krevs [20] studied the intensity of the Ljubljana UHI based on studies of long-term air temperature trends in Ljubljana and Zagreb. The intensity of the UHI in Ljubljana is said to have increased, especially after 1950. Komac et al. [21] published a study of UHI measurements in Ljubljana as a combination of satellite imagery and a comparison of temperatures and hot days between the city and its surroundings. They demonstrated an increase in the number of hot days and a decrease in the number of cold days in Ljubljana, as well as an internal differentiation of surface warming indicating a surface urban heat island (SUHI). Surface temperatures in the warmest parts of Ljubljana were higher than in the smaller cities around Ljubljana. In his study, Klemenčič [22] examined the use of remote sensing in changing the (S)UHI of Ljubljana and found that satellite imagery can be used to simulate surface warming, but the calculated surface temperature values need to be compared with the air temperature measured at weather stations.

The only study [6] that has examined the winter condition of the UHI in Ljubljana in more detail is 22 years old, but the methodology used then was different. Measurements at that time were based on the use of nine stationary stations for temperature measurements in the city and surrounding areas, and only one mobile temperature measurement in winter under ideal radiation weather conditions, one in summer, and one in autumn. The mobile measurements were made by driving in two teams. In this study, much more attention was also paid to wind conditions in the UHI and their effects on air quality in the city.

The aim of our study was as follows:

1. To present the temperature characteristics of the winter UHI in Ljubljana during radiation weather conditions using mobile measurements in a dense spatial network, since such a study has not been conducted before. In this way, much more accurate data were obtained on a denser spatial scale, and thus a more accurate picture of the winter UHI under radiation conditions. Our study also differs from previous studies of the UHI in Ljubljana, in that our results are based on a combination of mobile measurements in a dense spatial network (combination of car and bicycle measurements) and climatological measurements at stationary stations.
2. To compare the temperature profiles of the UHI obtained by mobile measurements in 2000 and 2022 to assess the change in UHI intensity over 22 years.
3. To combine the UHI intensity data with the urban population data to provide information on how many urban residents are exposed to the winter effect of the UHI in the radiation type of weather and to what extent. Winter UHI causes less cold stress, and fewer cold-related diseases; it also results in lower mortality of people exposed to cold (homeless people) [23], lower energy consumption for heat generation [24], and different ecological conditions in the city compared to the rural environment, such as a longer growing season, better conditions for insect life in winter, etc.

2. Study Area and Methods

2.1. Study Area

Ljubljana is the largest city and capital of Slovenia. It is located in temperate latitudes at the intersection of the Alps and Dinaric macroregion (Figure 1). The intersection of these macroregions is the Ljubljana Basin, and Ljubljana lies in its southern and almost lowest part at an altitude of about 300 m (Table 1). The surrounding peaks range from about 600 m above sea level in the southeast to over 2500 m in the north. The position of the basin and its leeward position with respect to the prevailing westerly winds of temperate latitudes is an important factor influencing the basin's lack of wind. In the cold half of the year especially, the Ljubljana basin often experiences temperature inversion and, as a result, fog [6,25]. In the second half of the 20th century, there were about 120 foggy days per year in Ljubljana, making it one of the foggiest cities in Europe. In recent decades, fog has decreased significantly. The average annual temperature for the period 1981–2010 was 10.9 °C [26], the coldest month was January with an average temperature of 0.3 °C, and the warmest was July with an average temperature of 21.3 °C [26]. The warming trend in Ljubljana is between 0.3 and 0.4 °C/10 years [27]. As in many other cities, the warming trend in Ljubljana is the result of a combination of climate change and the city's UHI effect that has existed for decades [6,20,21]. Despite the temperate continental climate, Ljubljana has a fairly humid climate. According to the data of the national meteorological network [26], the average annual precipitation is 1362 mm, precipitation is evenly distributed throughout the year, the wettest months are September, October, and June (147, 147, and 144 mm), and the driest months are January, February, and March (69, 70, 88 mm) [26]. Ljubljana Municipality has an area of 275 km^2 and 293,218 inhabitants [28], with a population density of 1068 [29]. In 20 years, the population has grown by 27,337 or 10.3% [30].

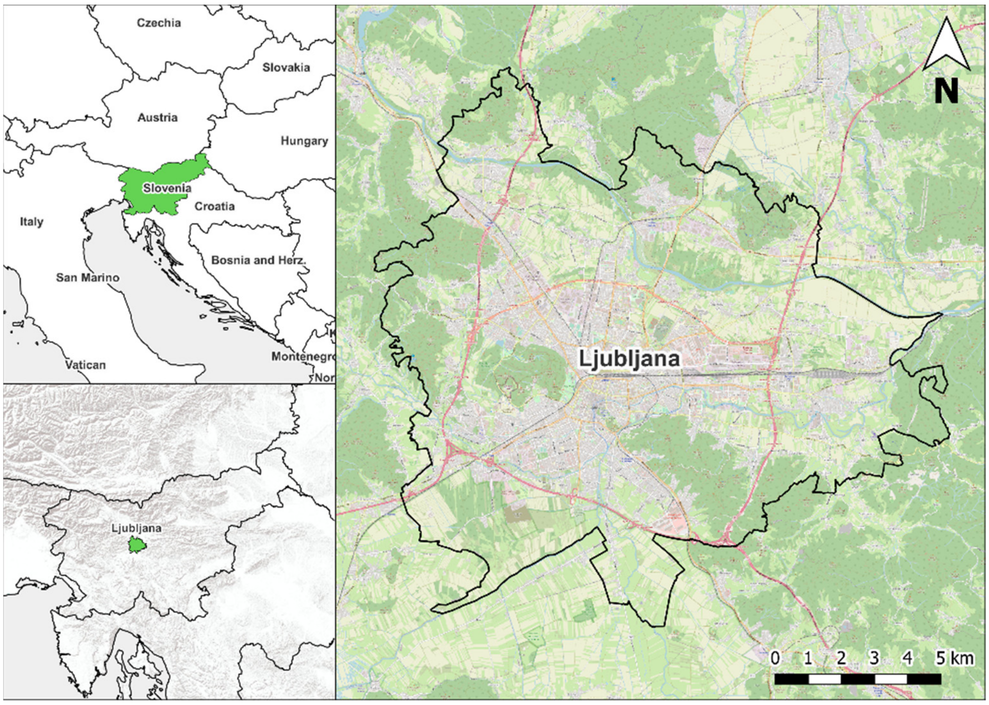

Figure 1. Location of area of research. Created by Domen Svetlin based on [31–34]. Used with permission and open access data.

Table 1. Metadata about the network of meteorological stations whose data were used in the research.

Station Name	Coordinates Φ, λ	Elevation (m)	Network
Scopolijeva Street	46.073931 N, 14.482441 E	304	University of Ljubljana
St. Stanislav Institution Šentvid	46.102036 N, 14.468873 E	314	University of Ljubljana
Črna vas Village	46.015019 N, 14.495461 E	288	University of Ljubljana
Vegova Street	46.053289 N, 14.498676 E	297	University of Ljubljana
SEA-Bežigrad	46.070084 N, 14.508194 E	299	National network of SEA
The Agricultural Institute of Slovenia	46.0605556 N, 14.5183333 E	297	Network of The Agricultural Institute of Slovenia
Šentjakob	46.0911824 N, 14.5731699 E	279	Network of The Agricultural Institute of Slovenia
Vnajnarje	46.0450272 N, 14.6719199 E	667	Network of The Agricultural Institute of Slovenia
Zadobrova	46.0670786 N, 14.5880529 E	280	Network of Energetika Ljubljana
Kleče	46.0861 N, 14.4997 E	307	National Network of SEA

2.2. Methods

The study was based on the combination of stationary and mobile temperature measurements and the analysis of temperature differences within the city during the radiation type of weather, i.e., when the sky is mostly clear and there is no significant advection

(Figure 2). Stationary measurements were used for permanent measurements in different parts of the city during the study period. They were carried out with automatic meteorological stations at four locations in the city and its surroundings. Data from the meteorological station of the Slovenian Environmental Agency Ljubljana (SEA) Bežigrad were also included in the study. For the interpolation of temperature values at the periphery of the study area, the temperature data from the existing stations of the agrometeorological network of Slovenia, the network of the company Energetika Ljubljana (electricity supplier), and the network SEA in the surroundings of Ljubljana were used. Subsequently, the UHI intensity data were combined with population data for the Ljubljana area to determine the exposure of the urban population to a given UHI intensity.

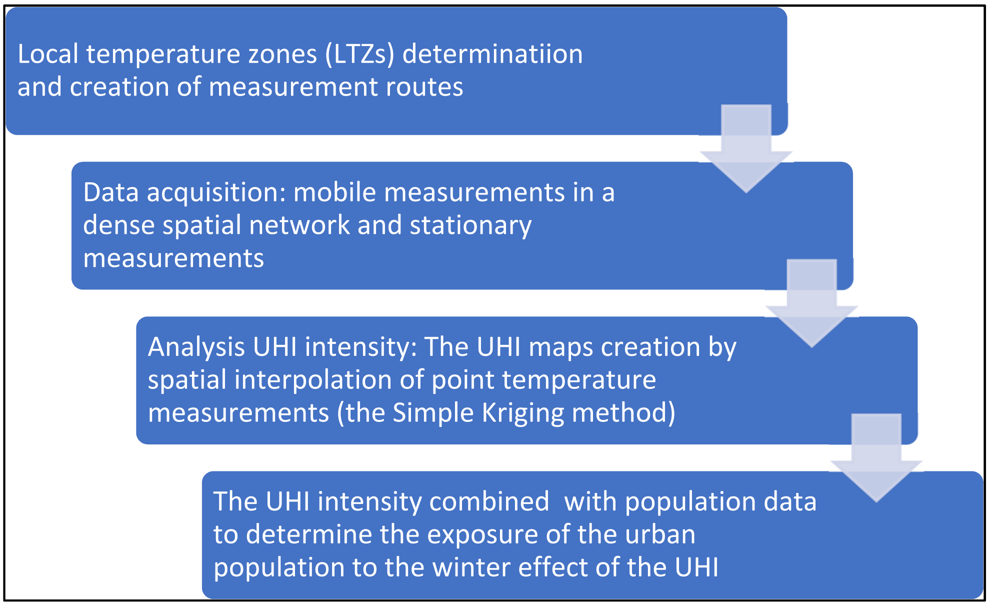

Figure 2. Methodological frame of study.

2.3. Mobile Measurements and Determination of Measurement Routes

Evening mobile measurements took place about one hour after sunset and morning mobile measurements about one hour before sunrise, i.e., when the thermometers' probes were not exposed to direct sunlight, or they were exposed to very weak solar radiation at sunrise, which did not affect temperature measurements significantly. Because of the high and dense buildings, there is still plenty of shade in the city even an hour after sunrise.

Nine measurements in meteorological winter, and two measurements in the first ten days of March, which otherwise already belongs to meteorological spring were conducted (Table 2). However, the weather in the first 10 days of March 2022 was very similar to weather in February 2022 or even colder, so we counted these 2 measurements as winter measurements. Altogether, six measurements in January, three in February, and two in March were conducted. Three measurements were conducted in the morning and the rest in the evening. The measurements were conducted so that four bicycle routes and one car route were formed, all of which were circular. The measurement routes (Figure 3) were established based on the theoretical determination of local temperature zones (LTZs) [35], in order to include all defined LTZs in field measurements. LTZs represent areas of homogeneous land cover and spatial characteristics, which is also reflected in related temperature features. LTZs were determined based on different spatial variables: Normalized Differential Vegetation Index (NDVI), Normalized Differential Built-Up Index (NDBI), area of buildings, height of buildings, surface roughness, albedo, and percentage of visible sky. The NDVI was calculated based on Sentinel satellite images, according to the classic NDVI formula (normalized difference). The NDBI was also calculated according to the classic formula of the normalized difference between the SWIR and NIR channels [36]. The area of buildings was calculated from the national Building Cadastre based on building polygons. The building height data were taken from the LiDAR point cloud-based digital surface model (DSM), using the highest point of the building. The surface roughness was also calculated from DSM using the Terrain Ruggedness Index (TRI) method [37]. The input for the albedo calculation was a Landsat satellite image that has been converted to Top of Atmosphere (TOA) reflectance. Liang's formula to calculate Landsat shortwave albedo which was normalized by Smith [38] was used for the calculation. The percentage of visible sky was calculated from digital terrain model using SAGA-GIS Sky View Factor Module.

Table 2. Dates of mobile measurements of winter UHI 2021/2022 in Ljubljana.

January 2022	February 2022	March 2022
6.1.	9.2.	2.3.
7.1.	23.2.	10.3.
12.1.	24.2.	
13.1.		
25.1.		
26.1.		

Blue highlights: morning measurements.

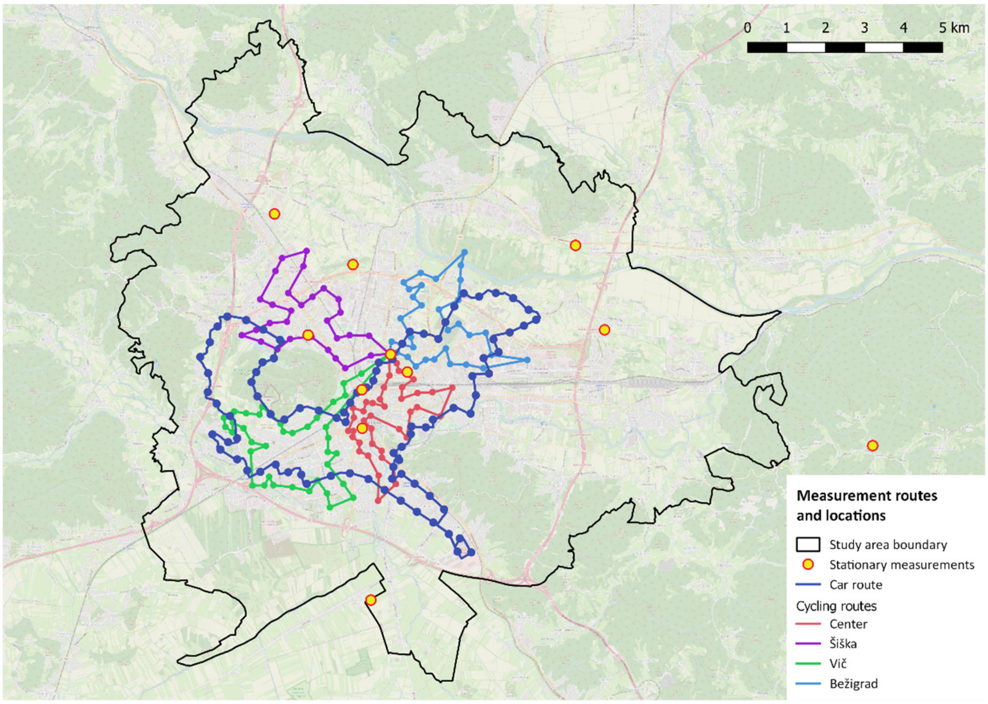

Figure 3. Measurement routes and location of stationary measurement points. Created by Domen Svetlin based on [31–34]. Open access data.

The study area was covered with two hexagonal grids of different resolution. The resolution of hexagons is defined as the radius of a circumscribed circle. A radius of 100 m was used for the inner part of the city (inside the Ljubljana ring road) and a radius of 250 m was used for the outer part. This was enacted due to the higher density of measurement points in the inner parts of Ljubljana. In each cell of the hexagonal grid, the average value of each previously mentioned variable was calculated. The calculations were performed separately for both grids. The calculation of average values of individual variables in all cells was followed by linear standardization of variables, with which a uniform measurement scale from 0 to 1 for all variables was determined. The standardization was performed with the Fuzzy Membership tool in ArcGIS. Then, an unsupervised classification of hexagonal grid cells was used, where a limit of 10 classes was set. The classification was performed using

ArcGIS Iso Cluster Unsupervised Classification tool, which performs unsupervised classification on a series of input raster bands. Based on the classification results, neighboring cells with the same class were merged into areas of homogeneous spatial characteristics. Some classes were very similar to each other in terms of land use, so we merged them together to make the study area less fragmented. The UHI maps were created by spatial interpolation of point temperature measurements using the Simple Kriging method. For the interpolation, both measurements from stations and mobile measurements were used. It was also necessary to ensure sufficient point density in the entire study area, including areas on the edges or outside the city where no measurements were conducted.

Spatially uniformly distributed random points were added in these areas and assigned temperature values according to the LTZ in which each point was located. For each measurement period, the average temperature of the respective LTZ was calculated from the available stationary and mobile measurements, which was then assigned to all newly added random points without data. In this way, the density of points was increased to account for the type of space in which each point was located when estimating the temperature in areas without measurements. Based on the air temperature layers, UHI intensity layers were created in such a way that for each measurement, the lowest measured temperature in the area was determined and the value obtained was subtracted from each cell within the area. Thus, the location with the lowest measured temperature received a value of 0 °C, and all locations with a higher temperature received the difference from the lowest temperature. The estimates of UHI intensity for a single season or measurement period (morning and evening) were calculated as the arithmetic mean of the measurements of each period, again considering the lowest calculated value as the starting point (0 °C). On each of the bicycle routes, two people conducted measurements by starting at the same point, then riding in opposite directions and measuring the temperature at the same points. They met in the middle of the route and continued in their own direction.

Thus, two temperature measurements were taken at each point. Each bicycle measurement took between 80 and 100 min, and each automobile measurement took about 2 h. The bicycle measurements were conducted with Testo 110 and Testo 175T3 digital thermometers; the response time of the probes was about 5 s. The resolution of the measurements was 0.1 °C, and the accuracy, according to the manufacturer, is between 0.2 and 0.3 °C [39] for the Testo 110 sensor and ±0.5 °C for the Testo 175T3 sensor [40]. The cyclists attached the thermometer probe to their bicycle handlebars and rode along the planned route from the first to the last measuring point. At the measurement point, they stopped, waited about 10 s, noted the temperature value, and continued riding. The car measurements were conducted with digital temperature recorders assembled specifically for this purpose, which store the readings, and also create a time record and geolocation of the measurement for each measurement (GPS coordinates). The accuracy of instruments was ±0.3 °C [41]. The measurements by car were conducted with a time resolution of 1 s, but only the temperatures of measuring points at a distance of 200–500 m from each other were used. Since the temperature at the site also changed during the period of measurements, it was necessary to correct the measured temperatures in time. Therefore, for each point, two measurements were made by surveyors traveling in opposite directions and meeting in the middle of the measured distance. The arithmetic mean of the two values was the temperature at a given point for the reference measurement time. The measurements by car were conducted in the same way. So, 10 people for each measurement, 8 on the bicycle routes and 2 on the car route were needed. In the cases where only one person measured on some routes, the measurements were corrected based on the temperature change at the reference measuring point (location SEA Bežigrad). The temperature change at the station SEA Bežigrad, which occurred during the elapsed time, was added to each temperature measurement on the route.

2.4. Stationary Temperature Measurements

Continuous measurements were conducted at 5 stations (4 stations within the University network and 1 station from the network of the SEA) in the city area for 70 consecutive winter days, after which 1 of the stations ceased operation. Therefore, for a general comparison, we provide temperature data from all stations for only 70 of 90 winter days, from 1 December 2021 to 8 February 2022.

3. Winter UHI Intensity and Discussion

3.1. Analysis of Data from Stationary Measurements

Stationary stations (Figure 4) in the urban area allowed us to constantly monitor temperatures and gain insight into air temperatures in different parts of the city. Table 3 shows significant differences in average temperatures between the city and the outskirts. The coldest station was located on the southern edge of the city in the Ljubljana Marsh in the village of Črna vas. There, the average temperature in the period under consideration was 0.5 °C, while on the northern outskirts of the city in Šentvid it was only a tenth of a degree warmer. The other stations in the city center or near it were significantly warmer, as the difference with the nearest station (Scopolijeva Street) was 0.7 °C, and another 0.3 °C with the station SEA Bežigrad. The warmest station was located on a closed street in the city center (Vegova Street), where the average temperature was 0.5 °C higher than at SEA Bežigrad, reaching 2.0 °C. Thus, at average temperatures of the stationary stations, the intensity of the winter UHI between the warmest and coldest station reached 1.5 °C. The order of the stations is the same, but there are larger differences in the average minimum temperatures, because here the difference between the coldest and the warmest station is 2.5 °C. The absolute minima (Table 4) again show the same sequence, following the pattern of weakening of the UHI toward the periphery, and the differences are the largest. The station Črna vas village has an absolute lowest temperature 4.5 °C lower than the station at Vegova Street, and the other stations are in between these values, but are closer to Vegova Street than the Črna vas village. A much smaller difference (1 °C) occurs in the average maximum temperatures, where the sequence does not follow the pattern of decreasing temperatures as one moves away from the city center. For absolute maximum temperatures (Table 4), the pattern is similar to that for average maximum temperatures. Again, the differences between the four stations are very small, with only the coldest station Šentvid deviating slightly, but even that only by less than 1 °C compared to the warmest station. No pattern of temperature decrease towards the outskirts of the city can be observed in the absolute maximum temperatures and average maximum temperatures, and it can be seen that the winter UHI becomes weaker during the day. For winter periods with snow cover, Žiberna and Ivajnšič [42] found that the daytime intensity of the SUHI is lowest in winter because the snow cover causes all types of land surfaces to have the same albedo. In our case, the diurnal intensity of the UHI is much lower compared to nocturnal measurements even without snow cover (Tables 3 and 4).

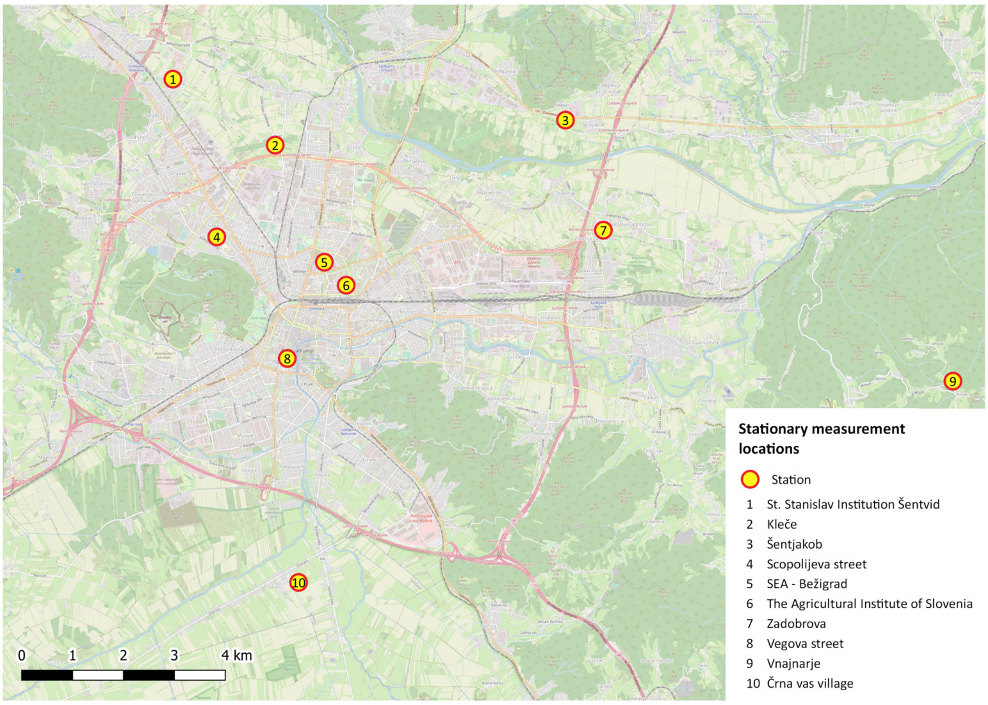

Figure 4. Locations of meteorological stations in the city and periphery. Created by Domen Svetlin based on [31–34]. Open access data.

Table 3. Average, average maximum, and average minimum air temperatures (°C) at stationary stations in Ljubljana from 1 December to 8 February 2022.

	Vegova Street	**Scopolijeva Street**	**SEA Bežigrad**	**Črna vas Village**	**Šentvid**
Tavg	2.0	1.2	1.5	0.5	0.6
Tavg min	−0.6	−2.0	−1.5	−3.1	−2.3
Tavg max	4.8	5.2	5.0	4.6	4.2

Table 4. Absolute maximum and absolute minimum air temperatures (°C) in Ljubljana between 1 December 2021 and 8 February 2022.

	Vegova Street	**Scopolijeva Street**	**SEA Bežigrad**	**Črna vas Village**	**Šentvid**
Tmin	−6.5	−8.0	−7.1	−11.0	−8.3
Tmax	13.6	13.7	13.4	13.7	12.9

3.2. Analysis of Data from Mobile Measurements

The mobile measurements provided us with a dense network of measurements that helped us create temperature differences in the city as a result of the UHI. At the beginning of each measurement, temperatures were measured at reference point 0 to check the reliability of the measurements. The mean standard deviation of all values was 0.5 °C, the highest 0.8, and the lowest 0.3 °C (Table 5).

Table 5. Standard deviations (°C) of temperature measurements at reference point 0.

Date	**6.1.**	**7.1.**	**12.1.**	**13.1.**	**25.1.**	**26.1.**	**9.2.**	**23.2.**	**24.2.**	**2.3.**	**10.3.**	**Avg.**
SD	0.3	0.6	0.4	0.5	0.2	0.8	0.3	0.8	0.5	0.4	0.5	0.5

For each point, the UHI intensity (°C) at that point was calculated for each measurement, and the standard deviation of the UHI intensity for all measurements at each point (°C) was determined (Table 6). The average standard deviation on each route was between 1 to 1.2 (°C), the minimum standard deviation between 0.7 and 0.9 °C, and the maximum standard deviation between 1.1 and 1.6 °C.

Table 6. Standard deviations (minimum, maximum, average) (°C) of UHI intensity of all measurement points at each measurement route.

	SD Avg.	**SD Min.**	**SD Max.**
Bežigrad	1.0	0.7	1.1
Center	1.2	0.9	1.5
Šiška	1.1	0.8	1.4
Vič	1.2	0.7	1.6

The winter morning UHI in Ljubljana (Figure 5) shows a maximum intensity of 5 °C. The area of >4 °C UHI intensity covers 1162 ha of the city, which is 7%. In total, 77,750 inhabitants live in this area, which is 27% of the total population of the city. A further 12,598 ha of the city, i.e., 77% of the city's area, is located in the 2–4 °C UHI intensity zone, and 200,642 inhabitants, i.e., 71% of the city's population, live in this zone. Only 2% of the population lives in the coldest zone, which occupies 16% of the city's area (2619 ha) (Table 7). On winter evenings, the UHI in the city center reaches an intensity of >4 °C in a very small area (1 ha) with no population. The area with a UHI intensity of 2–4 °C covers 3631 ha of the city, i.e., 22% of the area, and 183,409 inhabitants live in this area, i.e., 65% of the city's population. The coldest zone (0–2 °C) covers 12,747 ha or 78% of the city's area, and 99,709 inhabitants or 35% of the city's population live in this area (Table 7). Studies of the effects of UHI on human health or mortality have not yet been conducted for Slovenian cities, so we cannot assess the direct effects of milder temperatures on the health of urban populations. A study from London [43,44] found a 2% increased mortality rate for every 1 °C below the daily limit of 12 °C. Another UK study from the West Midlands region found, for the cold season of 2009/2010, that UHI reduced cold-related mortality by 15% [23].

Table 7. Area (ha) and share (%) of the city of Ljubljana, and the number and share (%) of inhabitants in each intensity zone of the UHI in winter 2020/21 in the morning and evening.

Morning UHI				
Temperature Zone	**Area (ha)**	**Population**	**Share of Area (%)**	**Share of Population (%)**
0–2 °C	2619	4726	16	2
2–4 °C	12,598	200,642	77	71
>4 °C	1162	77,750	7	27
Total	**16,379**	**283,118**	**100**	**100**
Evening UHI				
Temperature Zone	**Area (ha)**	**Population**	**Share of Area (%)**	**Share of Population (%)**
0–2 °C	12,747	99,709	78	35
2–4 °C	3631	183,409	22	65
>4 °C	1	0	0	0
Total	**16,379**	**283,118**	**100**	**100**

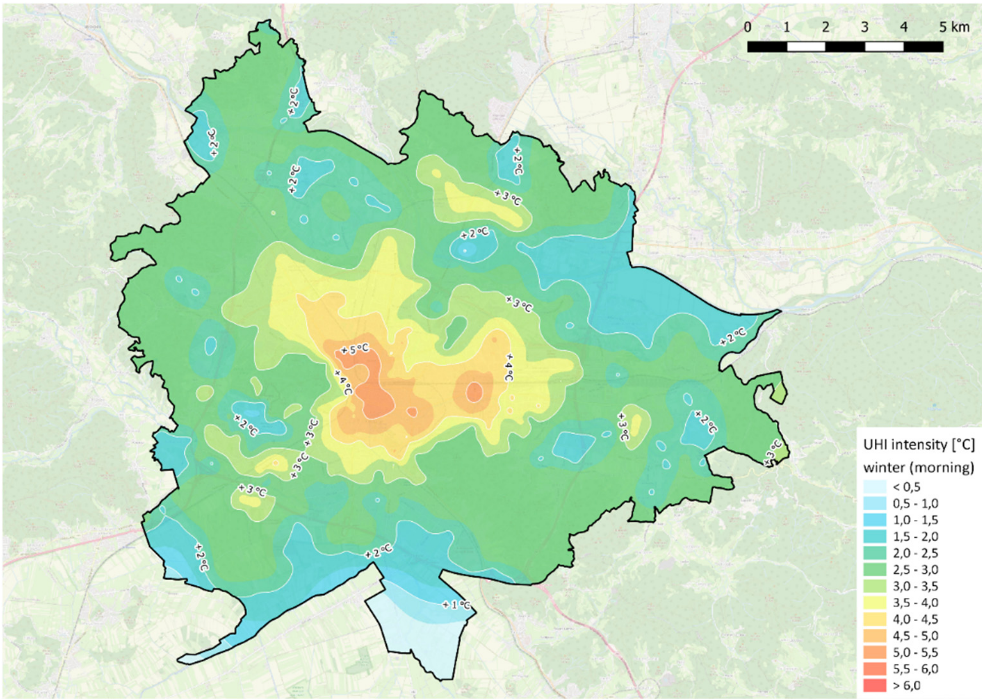

Figure 5. Intensity of the UHI in Ljubljana in the winter of 2021/2022 in the morning. Created by Domen Svetlin based on [31–34]. Open access data.

It is interesting to compare the morning (Figure 5) and evening (Figure 6) winter intensity of the UHI. In both cases it can be seen that the southern edge of the city at the Ljubljana Marsh is the coldest part, which was also confirmed by previous measurements [6]. However, the morning UHI is more intense and extended than the evening one, which deviates from the general pattern of the UHI, where the largest differences occur in the first half of the night [3]. This could be due to several factors. The first could be methodological, since there were significantly fewer measurements in the morning than in the evening. The lower number of measurements in the morning is due to the very frequent fog that occurs in Ljubljana in winter. When fog was present, the measurements were not carried out since we were focused on clear sky conditions to determine the UHI intensity during ideal conditions. On the other hand, the higher intensity in the morning may be due to the different radiation conditions and heat exchange between the atmosphere and the surface in the city and its surroundings. During the day, when the winter sun is low, the overheating of the surface in the city is low due to the low angle of solar radiation and greater shading. In addition, long-lasting morning fog often reduces it even further. Therefore, the differences in radiation accumulation between the surface in the city and the surface in the outskirts in the evening are not large, so the city center does not accumulate much heat during the day that it would radiate in the evening. At night, the surface around the city cools faster than the city center due to a greater sky view factor and less heat production. A significant part of the heat produced in the city is released to the environment in winter, resulting in higher temperatures in the more densely populated part of the city, which is also confirmed by other studies, e.g., [45,46]. A study from different towns at midlatitude, e.g., [8,47–51] also agree with smaller influence of solar radiation and suggests a stronger dependence of the outdoor winter temperature on climatic factors (wind, cyclonic weather patterns) than on site characteristics, e.g., albedo.

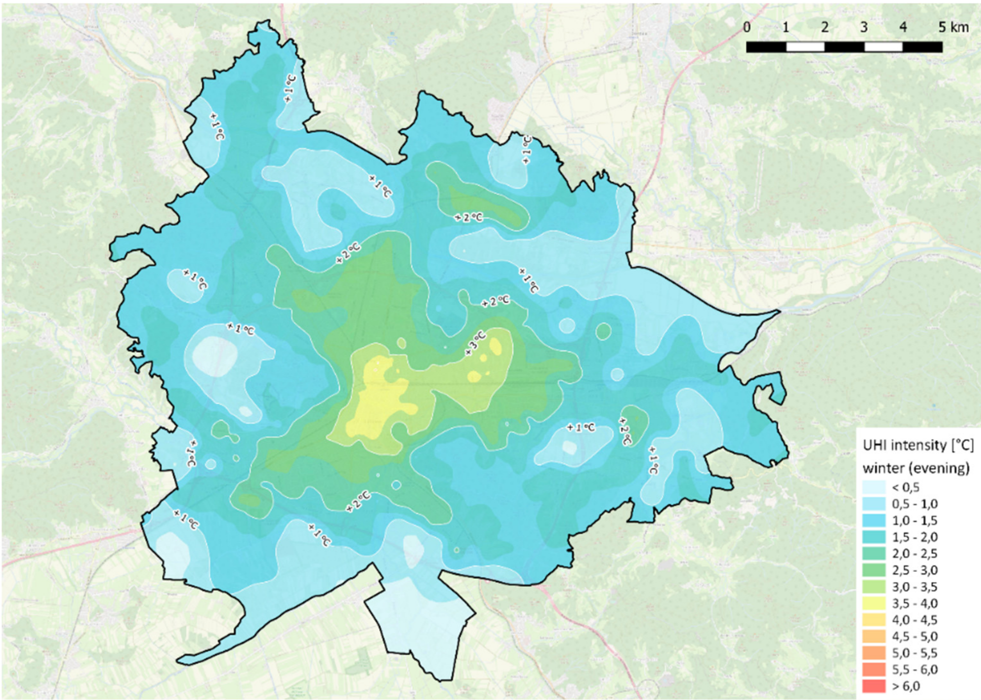

Figure 6. Intensity of the UHI in Ljubljana in the winter of 2021/2022 in the evening. Created by Domen Svetlin based on [31–34]. Open access data.

In our case, the cyclonic and advective weather type were eliminated, but there remains a small influence of variables directly related to solar radiation (albedo, heat storage), which is also confirmed by some studies [52,53]. The influence of solar radiation on the winter UHI decreases with increasing latitude and as the winter season approaches because the sun does not shine or shines weakly in high latitudes, and there is much shaded space in the city.

3.3. Comparison of UHI Intensity from 1998 to 2022

Although the intensity of the UHI of Ljubljana in the 1998, which is calculated from mobile measurements, is based on single measurements in winter during the radiation type of weather, we were interested in comparing the intensity of the UHI in winter 1998 and winter 2021/2022. It was concluded that the intensity in winter 2021/22 is significantly lower, reaching 4 °C, while in 1998 it was 7.4 °C. The main reason for this is the presence of snow cover, which was a common winter phenomenon in Ljubljana at that time, but is not anymore (Table 8). The measurements in 1998 took place on December 26 [6], when there was 17 cm of new snow in Ljubljana and cold weather with an average air temperature of −8.2 °C [54]. Even though this was only 24 years ago, winters in Ljubljana have warmed significantly during this period, which is confirmed by Table 8.

Table 8. Average number of days with snow cover in Ljubljana by decade [54].

Ljubljana	1961–1970	1971–1980	1981–1990	1991–2000	2001–2010	2010–2020
Number of Days with Snow Cover	76.9	58.6	59.1	47.9	50.5	29.5

The reason for the relatively low intensity of the UHI in the winter of 2021/2022 is the mild and largely snow-free winter. During the entire winter, there were only 28 days with snow cover, with a maximum thickness of 20 cm in December [54], when no measurements were taken due to mostly cloudy, rainy, and snowy weather. The 4 January measurements with a thin snow cover that did not exceed 6 cm of frozen snow in Ljubljana did not correspond to winter conditions as they did decades ago. Studies suggest that the colder the winters, the greater the UHI intensity appears to be, as heat production is then greater [3,24]. The positive effect of snow cover on winter UHI intensity was also confirmed by Yang et al. [55]. Their study of UHI in the northern Chinese city of Changchun found that UHI intensity was greater in winter than in summer (0.27 °C in summer and 0.40 °C in winter). Colder winters in temperate latitudes tend to have more snow, which also increases the urban UHI effect due to city snow management. In urban centers, snow is quickly cleared from some of the transportation infrastructure (roads, parking lots, pedestrian areas) and partly from roofs (due to melting as heat is lost from buildings), while in surrounding areas, the snowpack remains untouched for long periods of time, which further enhances the UHI effect in winter (Figure 7). On the other hand, winters in Ljubljana have become much milder in the last two decades, and this trend will continue, as there is no end in sight to global warming. It can be concluded that the winter of 2021/2022 was quite common for modern winters, despite the very small amount of snow and the short duration of the snow cover. Due to climate change, winters today are much milder than the ones that were in Ljubljana two or more decades ago, but at the same time this winter was colder than the winters one can expect in future decades. It can be concluded that one of the consequences of climate change is a less pronounced UHIs in winter, as there is less snow and less heat needs to be generated to heat buildings.

Figure 7. Snow-covered Ljubljana's periphery in 2010. A thick and long-lasting snow cover, which has a great impact on the formation of the winter UHI, has become a real rarity in Ljubljana in the last decade. The decrease in snow cover has a strong influence on the weakening of the winter UHI in Ljubljana. Photo took by Matej Ogrin.

4. Conclusions

Stationary measurements of the temperature of the winter UHI in Ljubljana showed the expected temperature drop towards the less built-up periphery of the city at average air temperatures with an intensity of 1.5 °C compared to the warmest station. These differences were even larger for the average minimum temperatures (2.5 °C). This pattern is not maintained for average maximum temperatures, where temperatures in the periphery do not differ significantly from those in the city. In winter, the morning UHI in Ljubljana was shown to be more intense and bigger than the evening UHI, which may be due to several factors. The first one could be methodological, since there were significantly fewer morning measurements than evening measurements. On the other hand, the higher intensity in the morning may be the result of different radiation conditions and heat transfer between the atmosphere and the surface in the city and its surroundings. During the day, when the sun is in its winter position, the overheating in the city is low (in addition to the low sun, this is also because of the frequent fog and shading), so the differences between heat accumulation of surfaces in the city and in the periphery in the evening are not large. At night, the differences in heat radiation and heat production between the city and its periphery are greater, so the UHI intensity increases. In winter radiative type of weather, the warmest part of Ljubljana reaches an intensity of 3.5 °C in the evening. In total, 22% of the city's area is in the evening UHI intensity range of 2–4 °C, and 65% of the city's population lives in this area. In the morning, the UHI in Ljubljana shows a maximum intensity of 5 °C. The area of >4 °C UHI intensity covers 7% of the city's area, and 28% of the total city population lives in this area. 77% of the city's area is in the 2–4 °C UHI intensity zone, and 71% of the city's population lives in this zone. Higher winter temperatures bring less cold stress to urban population, especially during extremely cold winter periods [46,56,57].

The shortcomings of our research were due to unfavorable weather conditions in the first part of the winter (December), when a somewhat thicker snow cover appeared, but the weather was cloudy with frequent precipitation and fog. Another shortcoming was the uneven distribution of measurements between night and morning measurements in favor of evening measurements. For future research, it would also be very useful to conduct stationary wind measurements with high-sensitivity anemometers in the city to see how the UHI affects local air dynamics at very low speeds within the city and influences the transport and dispersion of pollutants in the local urban atmosphere.

The first major study of the UHI in Ljubljana was published in 2000. A comparison of our results with the results of this study is only possible to a limited extent due to the different methodology. In both cases one can conclude that Ljubljana Marsh (the southern edge of Ljubljana) remains the coldest area of the city. A notable difference in both cases is the intensity of the UHI in winter. It seems that the winter UHI in Ljubljana is weakening, which is a consequence of climate change and increasingly milder and greener winters in Ljubljana.

There are a number of mitigation measures for UHI effects that are particularly important in summer to mitigate heat stress, and less so in winter when the UHI effect can be actually beneficial for the city's population. The consequences of UHI in winter are lower energy consumption for heating buildings and fewer cold-related deaths; some measures which mitigate the summer UHI intensity can lead to increase cold-related stress in winter. In severe cold regions of China, UHI reduces annual energy consumption and temperature-related mortality due to higher UHI intensity in winter compared to summer [24]. Studies in the UK show that cold mortality in a heavily urbanized region of the West Midlands (including Birmingham) is larger than heat mortality and UHI attributed to 266 fewer deaths in winter. With future climate projection, winter-cold-related deaths are expected not to change significantly, while summer-related deaths are expected to increase and slowly close the gap to winter-related mortality by 2080 [23]. Therefore, when planning UHI mitigation measures, one must always start from the local UHI characteristics and, in addition to the summer characteristics, also know the winter UHI characteristics and their impact on the health of the population.

Author Contributions: Conceptualization, M.O. and B.L.; Methodology: B.L., M.O. and S.S.; Formal analysis: D.S. and M.O.; writing—original draft preparation: B.L. and M.O.; writing—review and editing: B.L., M.O., D.S. and S.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Municipality of Ljubljana, project contract number C7560-21-110266, and Slovenian Research Agency, P6-0229 Sustainable Regional development of Slovenia (Tranjostni regionalni razvoj Slovenije).

Data Availability Statement: The data presented in this study are available on request from the Municipality of Ljubljana.

Acknowledgments: Thanks go to Iztok Miklavčič for research assistance and to Pileus company for providing stationary stations. Polona Marinček and Rajko and Vera Kos for their help in providing the locations of stationary stations. The same goes for the management of Vegova Upper Secondary School of Electrical and Computer Engineering and Ljubljana Technical High School, and the management of St. Stanislav's Institution, as well as to the students and all others who helped with the mobile measurements.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

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