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Data-driven characterization of urban heat island intensity, heat wave, and heat stress interactions in Brussels: A field measurement study

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ABSTRACT

Urban configuration and climate change both impact the local climate conditions and outdoor thermal comfort. This study examines summer Urban Heat Island (UHI) intensity and thermal discomfort in the Brussels region using a data-driven approach based on continuous field measurements collected from July to September 2022. The characterization of near-surface UHI revealed strong temperature elevations, reaching up to 19°C between four urban sites and one suburban area during several periods. Based on the Humidex index, these UHI intensities caused significant heat stress, affecting people's thermal comfort, resulting in more than 38 hours of intense discomfort across 60 days in summer 2022. Within a period of less than three months, three heat waves occurred in proximity, which also amplified UHI by 2°C at nighttime and 1°C during the day compared to normal climatological days. Results led to a real characterization of UHI levels and their effects on one of the EU cities. By identifying UHI hotspots and thermal discomfort zones, urban planners can prioritize interventions such as increasing green spaces, implementing cool roofs, and developing an early warning system to protect vulnerable populations during extreme heat periods.

1. Introduction

1.1. Background

The phenomenon of Urban Heat Island (UHI) has emerged as a pressing environmental concern in an era defined by rapid urbanization. Cities, with their dense infrastructure and reduced natural surfaces, tend to trap heat, resulting in significantly higher temperatures than in surrounding rural areas (Kim and Brown, 2021, Matallah et al., 2023)[1]. This effect is particularly evident during heat waves, which are becoming more frequent and intense due to climate change (He et al., 2021).

Relevant studies listed in Table 1 have extensively explored the complex interplay between climate change, heat waves, and urban heat islands UHI, revealing significant impacts on urban environments and human health. Researchers have employed various methodologies, including remote sensing, climate modeling, and social media data analysis, to understand these phenomena better and develop strategies for mitigation and adaptation.

In this regard, many studies have focused on characterizing heat waves and projecting their future trends. A study conducted by Ouzeau et al. (2016) (Ouzeau et al., 2016) developed a new method for analyzing heat waves based on the high quintiles of daily temperature distributions, projecting an increase in the frequency, duration, and intensity of heat waves in France under future climate conditions. Similarly, Singh and Mall (2023) (Singh and Mall, 2023) investigated

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[1] The references' citations in blue, specifically those between brackets throughout the manuscript, should appear as numbers.

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Table 1
Summary of recent studies on the interplay between climate change, heat waves, and urban heat islands.

Author(s)	Year	Case study	Size of the studied area	Region, Climate or Köppen classification	Study focus
Ouzeau et al. (Ouzeau et al., 2016)	2016	France	Entire country	Varied (Cfb, Csa, Csb, Cfa)	Heat waves Climate change EURO-CORDEX Regional modeling
Singh & Mall (Singh and Mall, 2023)	2023	India	Entire country	Varied (Aw, Bsh, Cwa, etc.)	Heat waves Climate projections CORDEX Vulnerability assessment
Li et al. (Li and Chen, 2023)	2023	561 global cities	Global scale	Multiple Köppen climate classifications	Surface urban heat island Heat wave Indicator-based variations Factor analysis Surface energy changes
Miao et al. (Miao et al., 2022)	2022	354 Chinese cities	National scale (China)	Multiple climate zones in China	Surface urban heat island Heat wave Land surface temperature MODIS Climate variability
Buscail et al. (Buscail et al., 2012)	2012	Rennes, France	50.36 km²	Cfb (temperate oceanic climate)	Heat wave risk Remote sensing Vulnerability mapping Urban planning
Savić et al. (Savić et al., 2018)	2018	Novi Sad, Serbia	112 km²	Cfb (temperate, fully humid, warm summer)	Urban heat island Risk assessment Local climate zones Mortality
Shafiei Shiva et al. (Shafiei Shiva et al., 2022)	2022	Maricopa County, Arizona, USA	Not specified	BWh (hot desert climate)	Heat wave hazard Multi-criteria decision making Urban areas Hazard mapping
Papathoma-Koehle et al. (Papathoma-Koehle et al., 2016)	2016	Arad, Romania	City of Arad (population ~160,000)	Cfb (temperate oceanic climate)	Heat waves Risk assessment Vulnerability mapping Urban areas
Wang et al. (Wang et al., 2021)	2021	China's megacities	31 provincial capitals and municipalities	Various across China	Heat wave Spatial heterogeneity Urban heat island
Durgun & Håkansson (Durgun and Håkansson, 2020)	2020	Lerum and Trelleborg, Sweden	27.93 km² (combined)	Cfb (temperate oceanic climate)	Heat waves Urban Heat Island Remote sensing Municipal services
Ji et al. (Ji et al., 2024)	2024	Shenyang, China	Main districts of Shenyang	Dwa (Köppen) - Cold, dry winters and hot, rainy summers	Thermal comfort Heat waves Urban morphology Climate change adaptation
Côté et al. (Côté et al., 2024)	2024	Montreal, Quebec, Canada	City of Montreal	Not specified, but Montreal has a humid continental climate	Heat waves Mortality Climate projections Vulnerability assessment
Nardino et al. (Nardino et al., 2022)	2022	Bologna, Italy	105.8 km²	Cfa (Köppen) - Humid subtropical climate	Urban heat wave Thermal index Remote sensing Urban climate
Liu et al. (Liu et al., 2023)	2023	Huzhou, Jiaxing, Hangzhou, and Ningbo, China	4 cities	Cfa (humid subtropical climate)	Urban Heat Island Remote sensing Heat wave risk Temperature mapping
Mohammad et al. (Mohammad and Weng, 2024)	2024	Review of global heat wave definitions and metrics	N/A - Review paper	Various - covered global definitions	Heat waves Definitions Metrics Climate extremes

(*continued on next page*)

Table 1 (*continued*)

Author(s)	Year	Case study	Size of the studied area	Region, Climate or Köppen classification	Study focus
Barriopedro et al. (Barriopedro et al., 2023)	2023	Review of global heat wave research	N/A - Review paper	Various - covered global research	Heat waves Physical drivers Climate change Scientific challenges
Marx et al. (Marx et al., 2021)	2021	Literature review of global heat wave research	N/A - Literature review	Various - covered global research	Heat waves Climate change Bibliometric analysis Research trends
Gilabert et al. (Gilabert et al., 2021)	2022	Barcelona, Spain	636 km^2 (Metropolitan Area)	Cfb (temperate oceanic climate)	Urban Heat Island Local Climate Zones Heat exposure Climate modeling

future changes in heat wave characteristics across India, identifying Northwestern, Central, and South-central India as future heat wave hotspots.

Understanding how urban heat islands interact with heat waves events has emerged as a critical research priority in urban climate science. Li and Chen, 2023 (Li and Chen, 2023) conducted a comprehensive global study across 561 cities, finding that daytime surface urban heat island (SUHI) intensity generally decreased during heat waves, while nighttime SUHI intensity increased. Additionally, Miao et al., 2022 (Miao et al., 2022) further investigated this phenomenon in 354 Chinese cities, revealing that SUHI was augmented in humid regions but diminished in arid areas during heat waves, with rural vegetation coverage playing a crucial role.

On the other hand, several researchers have developed methodologies for assessing and mapping heat wave risks in urban areas. Buscail et al., 2012 (Buscail et al., 2012) developed a heat wave health risk index for Rennes, France, combining satellite thermal data and census information. Although Savic et al., 2018 (Savić et al., 2018) conducted a similar study for Novi Sad, Serbia, they found that densely built-up areas had very high- or high-risk values. A study done by Shafiei et al., 2022 (Shafiei Shiva et al., 2022) presented a novel multi-criteria decision--making approach for mapping heat wave hazards in Maricopa County, Arizona, USA, revealing that the northern and central parts of the metropolitan area were subject to heat wave. Papathoma-koehle (Papathoma-Koehle et al., 2016) presented a method for climate hazard risk assessment in Southeast Europe, applied to heat wave risk in Romania, and developed hazard and impact maps using temperature and intervention data. Moreover, Wang et al., 2021 (Wang et al., 2021) examine heat wave exposure and sensitivity in Chinese megacities using social media, temperature data, and developed methods to extract heat events from various data sources. The study of Durgun and Hakansson, 2020 (Durgun and Håkansson, 2020) presented a method for mapping urban heat islands using remote sensing, identified hot spots and vulnerable municipal services in Swedish cities, and demonstrated that urban heat effects occur in cooler climates.

Complementary research initiatives have increasingly focused on developing practical solutions to enhance urban thermal comfort during heat wave, recognizing the urgent need for climate adaptation strategies. Ji et al., 2024 (Ji et al., 2024) developed a hierarchical thermal comfort-optimized network for Shenyang, China, integrating network and patch morphology approaches to identify key areas for thermal comfort optimization. Their study emphasized the importance of considering differentiated interactions among landscape indices at various levels to enhance thermal comfort optimally.

Furthermore, other studies have examined vulnerability and exposure to heat waves in urban environments. Côté et al., 2024 (Côté et al., 2024) projected heat wave risks and vulnerability for Montreal, Canada, incorporating factors such as age, socioeconomic variables, and vegetation cover.

On the other hand, researchers have developed new indices and methodologies to quantify heat waves and their impacts better. The study conducted by Nardino et al., 2022 (Nardino et al., 2022) proposed a new Urban Heat wave Thermal Index (UHTI) to quantify daytime air temperature variability during heat waves in Bologna, Italy. When, Liu et al., 2023 (Liu et al., 2023) introduced a novel approach for dense temperature mapping and heat wave risk analysis based on multisource remote sensing data in four Chinese cities. Mohammad and Weng (2024) (Mohammad and Weng, 2024) compared heat wave indices to identify dangerous conditions across various climates. Results showed that the lethal heat stress index performed best in low-humidity environments, highlighting a need for a global heat wave framework.

Barriopedro et al. (2023) (Barriopedro et al., 2023) provided a comprehensive review of the physical understanding and scientific challenges related to heat waves, highlighting the need for process-based understanding to improve forecasts, trend attribution, and regional climate projections. Additionally, Marx et al. (2021) (Marx et al., 2021) conducted a bibliometric analysis of the rapidly growing scientific literature on heat waves, identifying key themes and citation classics in the field.

1.2. Research gaps in urban heat island (UHI) studies

Despite these advancements, several knowledge gaps persist. There is a notable lack of long-term field measurement studies, with many researchers relying heavily on remote sensing or modeling approaches. This limitation hinders the validation and refinement of existing models across diverse urban contexts. Additionally, the lack of standardized methodologies for studying UHIs and heat waves makes cross-city comparisons challenging, hindering the development of a comprehensive global understanding.

A significant geographical bias exists in current research, with limited exploration of UHI dynamics in European urban environments compared to global patterns or Asian contexts. Furthermore, there is insufficient focus on mid-sized cities, as much of the existing research concentrates on megacities or large metropolitan areas. This leaves a gap in understanding how UHIs and heat waves manifest in smaller urban areas, which may have unique characteristics and challenges.

While some studies have begun to explore the interactions between UHIs and heat waves, there is still a need for more in-depth analysis of how heat waves specifically modify UHI patterns and intensities, particularly in temperate oceanic climates. Many studies focus primarily on temperature, without fully incorporating humidity and other factors that affect human thermal comfort, necessitating a more comprehensive analysis using established thermal comfort indices.

Lastly, there is a lack of tailored, location-specific adaptation recommendations based on detailed UHI characterizations. This gap is particularly evident in the lack of city-specific UHI characterization in many urban areas, which is crucial for local urban planning and heat mitigation strategies. Addressing these knowledge gaps requires interdisciplinary approaches that integrate climate science, urban planning, and public health to develop more effective adaptation and mitigation strategies for our increasingly urbanized world.

Brussels, the capital city of Belgium, is no exception to this global trend, offering a critical case study for UHI research. Brussels is characterized by a temperate oceanic climate (Köppen climate classification: Cfb), with warm summers and cold winters (Amaripadath et al., 2022). The city's densely built environment, with a high proportion of impervious surfaces, contributes to heat retention and exacerbates the UHI effect (Amaripadath et al., 2023). Studies by (Lauwaet et al., 2024)[2], have shown that Brussels experiences significant temperature differences between urban and suburban areas, particularly during the summer season. Understanding the spatial and temporal patterns of UHIs in Brussels is crucial for developing effective mitigation strategies to protect citizen health and improve urban livability.

The impact of UHIs on public health and the urban environment is not to be underestimated. Elevated temperatures can exacerbate existing health conditions, increase heat stress, and stroke risk, and contribute to air pollution through the formation of ground-level ozone (Arrar et al., 2024, Matallah et al., 2020). Recent studies by (Ballester et al., 2023, Chaston et al., 2022, Song et al., 2024, Xu et al., 2016) demonstrate a correlation between UHI intensity and heat wave-related mortality, highlighting the urgency of addressing this issue. Furthermore, He et al. (2022) (He et al., 2022) emphasize the economic consequences of UHI effects, including increased energy consumption for cooling buildings and infrastructure damage resulting from extreme heat events. While the existence of UHIs in Brussels is well established, a comprehensive understanding of their intensity and spatial distribution remains elusive. Existing research often relies on limited data sources, such as weather station observations, which may not capture the fine-scale variations in temperature within the city. Additionally, traditional methods for UHI characterization, such as the simple urban-rural temperature difference, may not fully account for the complex interplay of factors influencing urban thermal environments (Degefu et al., 2022, Silva et al., 2021).

Furthermore, studies by Castro Silva et al. (2021) (De castro Silva and CAVALCANTE, 2021) and Diaconescu et al. (2023) (Diaconescu et al., 2023) emphasize the importance of considering metrics beyond temperature alone when evaluating thermal comfort in urban settings. The Humidex index, which combines temperature and humidity, offers a more comprehensive measure of heat stress and can be a valuable tool for UHI studies. In addition, it is particularly useful for assessing outdoor thermal comfort, especially in high summer temperatures, and is widely used by Canadian authorities (Sahabi-Abed and Kerrouche, 2017). This index has been a valuable tool in assessing perceived heat stress in Brussels, where the UHI effects exacerbate thermal discomfort during heat waves (Timmermans et al., 2024).

Previous work on UHIs in Belgian cities has laid the groundwork for understanding the spatial distribution and the factors influencing them nationwide. Therefore, a study conducted by Lauwaet et al. (2016) investigated the UHI intensities in the current and future scenarios within the Brussels agglomeration and is based solely on a simulation model at a 250 m resolution (Lauwaet et al., 2016). A second significant study, conducted in 2020, mapped urban cool/heat islands in the city of Ghent, Belgium, using the Wet Bulb Globe Temperature (WBGT) as the primary climatic parameter to simulate heat stress at an urban agglomeration resolution of 100 m (Lauwaet et al., 2020). In fact, numerical modeling has also been employed continuously to estimate UHI intensities, highlighting the role of urban characteristics in UHI mitigation (Mills et al., 2022). These studies have contributed to the existing body of knowledge, but they have limitations in terms of data sources, methodological approaches, and the accuracy of estimating UHI effects at the micro-scale.

In this context, we identified a need to provide an overview of UHI characterization and intensity in the Brussels Capital Region, Belgium, which is experiencing rapid urbanization and population growth, particularly among older demographics. This paper aims to address the following research questions:

1. How do high-resolution in-situ measurements characterize the spatial and temporal variations of UHI intensity across Brussels during the summer months?
2. To what extent do heat waves amplify the near-surface UHI intensity, and how does this thermal amplification affect pedestrian outdoor thermal comfort?

To address these questions, this study proposes a robust methodological approach for estimating UHI intensities in Brussels. The proposed approach employs data-driven statistical analysis and thermal mapping to offer a nuanced understanding of heat stress during the summer and heat waves. Specifically, the study establishes a network of weather stations across the Brussels Capital Region to capture the spatial variability in temperature and humidity. Statistical analysis techniques such as ANOVA will be employed to identify factors contributing to near-surface UHI variations, including land cover type, building density, and surface characteristics.

In the systematic review conducted by Deilami et al., 2018 (Deilami et al., 2018) on the effects of UHI, 54.6 % of studies used Landsat TM images, followed by Landsat ETM+ (34.6 %) and MODIS (28 %), which are types of remote sensing (satellite) data. As reported in the study of Mirzaei and Haghighat, 2010 (Mirzaei and Haghighat, 2010), remote sensing is a very expensive approach, and it is not possible to obtain steady images of the urban near-surface, which is partly related to the accuracy of the used apparatuses and partly due to atmospheric interactions. To the best of our knowledge, most studies investigating UHI intensity focus solely on the Land Surface Temperature (LST) as the leading indicator calculated from satellite-measured radiation, which is not fully representative of near-surface UHI variations.

Furthermore, the study develops high-resolution thermal maps of Brussels using the collected data to visualize the spatial distribution of UHI. It reveals the concrete interaction of heat waves and UHI intensity. Notably, the study assesses the effectiveness of the Humidex index by evaluating thermal comfort and its correlation to UHI intensity. The findings of this study will not only contribute to the existing body of knowledge but also provide practical insights for urban planners and policymakers, drawing from the latest research on heat waves and their urban impacts.

The proposed methodology can be adapted and applied to other cities with similar climatic conditions, fostering a broader understanding of UHIs and promoting the development of effective adaptation measures across urban environments. By addressing gaps in current knowledge and leveraging advanced techniques, this study aims to provide an accurate assessment of current near-surface UHI intensities in Brussels, to draw a roadmap for suitable mitigation strategies and to enhance urban resilience in response to climate change.

2. Methodology

The research methodology comprises three main stages, with climate field measurements serving as the key data for UHI characterization. As shown in Fig. 1, an overview of the study's conceptual framework is explained as follows:

1. Firstly, in situ field measurements of multi-climate parameters throughout urban and suburban areas within the Brussels Capital Region from July to September 2022.
2. Secondly, using a data-driven approach, the near-surface urban heat island (UHI) intensities and their thermal effects are characterized on normal and heat wave (HW) days to identify hotspots within the study area. At this stage, the exploration of results identified an alarming situation: apparent thermal fluctuations, and high levels within the study context, which are representative of many EU cities.

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[2] 2024 in the place of 2022.

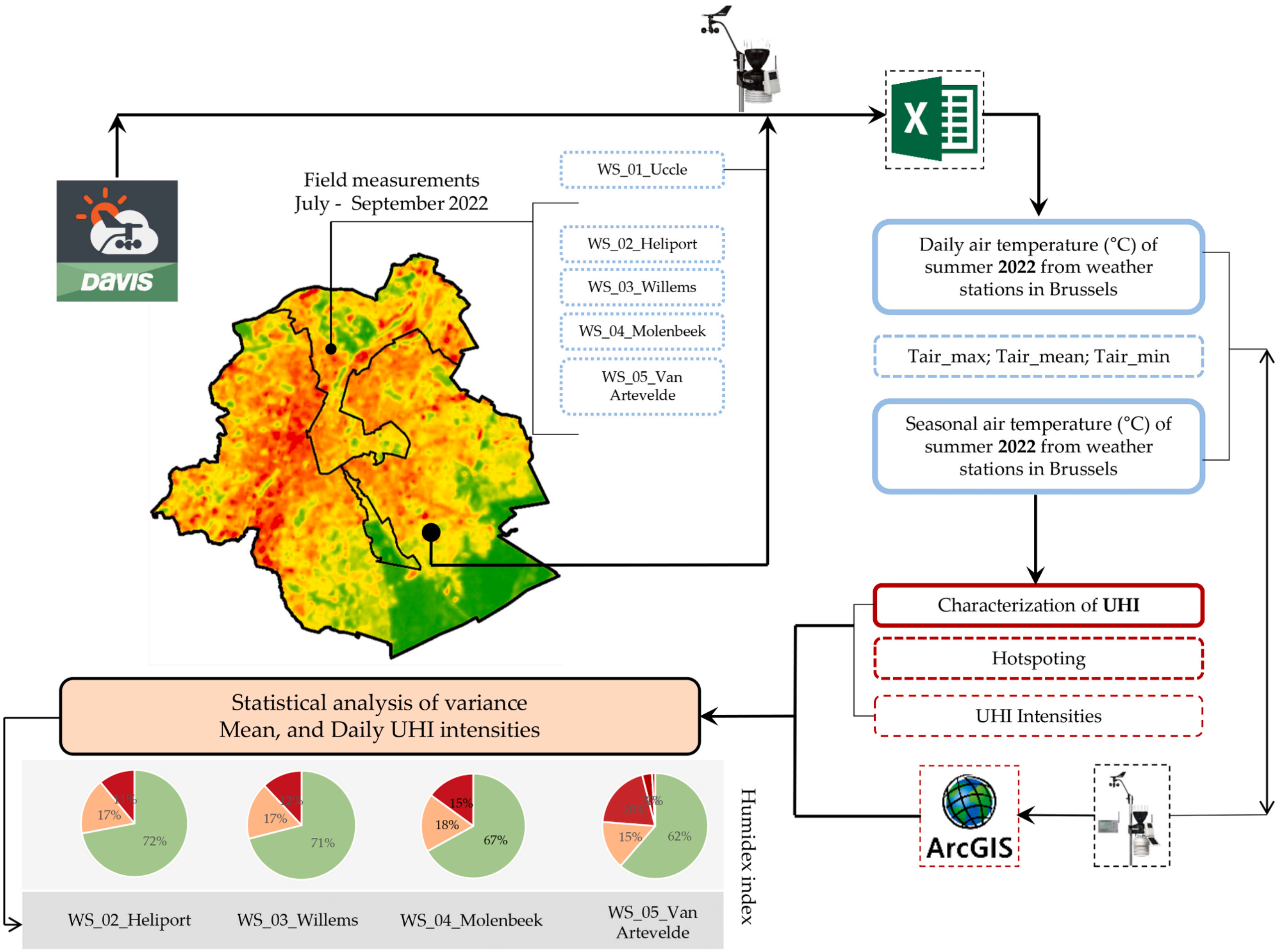


Fig. 1. Study conceptual framework.

3. Thirdly, an evaluation of the outdoor thermal comfort influenced by the UHI intensities and HW based on the Humidex index. A statistical analysis was conducted to evaluate the correlation among climate parameters, UHI intensities and outdoor thermal comfort.

Accordingly, in the methodology section, it was necessary to introduce multiple data analysis methods for assessing UHI intensity, including thermal mapping and statistical analysis.

2.1. *Study area & summer extreme weather conditions*

The Brussels Capital Region is located in the north-central part of Belgium, encompassing the Capital city of Brussels. With approximately 1,222,637 inhabitants in 2022 spread over 19 municipalities on 162 km^2, the region is characterized by a high population density (7528 inhabitants/km^2) that makes it the biggest agglomeration of the country. The commune of Brussels (in orange), represents the study area, and is situated in the northern part of the Capital Region, as shown in Fig. 2.

Based on Köppen-Geiger climate classification, Brussels experiences a temperate maritime climate (Cfb). From 1949 to 2023, the Brussels Capital Region experienced a daily average minimum temperatures during winter of -2.2°C, and a daily average maximum temperature during summer of 25°C. Otherwise, the yearly temperature daily average is about 10.7°C (Center for the Built Environment (CBE) Clima). Accordingly, by night, the maximum average temperature can reach about 26.3°C, and the minimum average of -4.6°C. In contrast, the diurnal maximum average temperature is about 30.7°C, while the minimum average is about -4.8°C (Center for the Built Environment (CBE) Clima). In the Brussels area, the average maximum temperature can exceed 30°C during heat wave days, which increases the humidity rate inside the city and makes it very uncomfortable. A study conducted by De Troeyer et al., 2020 (De Troeyer et al., 2020) showed a 3.5 % increase in mortality rate between 2002 and 2011, equivalent to 1585 deaths per 1°C increase in temperature in Brussels city during extreme summer conditions. Moreover, a study by Demoury et al., 2022 (Demoury et al., 2022) investigated the mortality risk associated with exposure to extreme temperatures in the period from 2010 to 2015 in 9 Belgian cities. Results indicated that people aged 65 years old and above, living in built-up municipalities, were at a higher risk during heat events, and women were more vulnerable to heat than men. Brussels and Antwerp were the most affected agglomerations by summer high temperatures. In another study conducted by Amaripadath et al., 2023 (Amaripadath et al., 2023), Charleroi in Belgium, has also experienced severe heat waves during the last few decades.

2.2. *Heat wave*

Defining heat waves universally is challenging due to varying climatic conditions and socio-demographic factors that exist worldwide. According to the Royal Meteorological Institute (RMI) of Belgium, a heat wave is a period of at least three consecutive days with a mean minimum temperature above 18°C and a mean maximum temperature above 30°C (Hamdi et al., 2016).

In the Netherlands, a neighboring country to Belgium, the Royal Netherlands Meteorological Institute (KNMI) defines a heat wave as a period of at least 5 (five) consecutive days with a maximum air

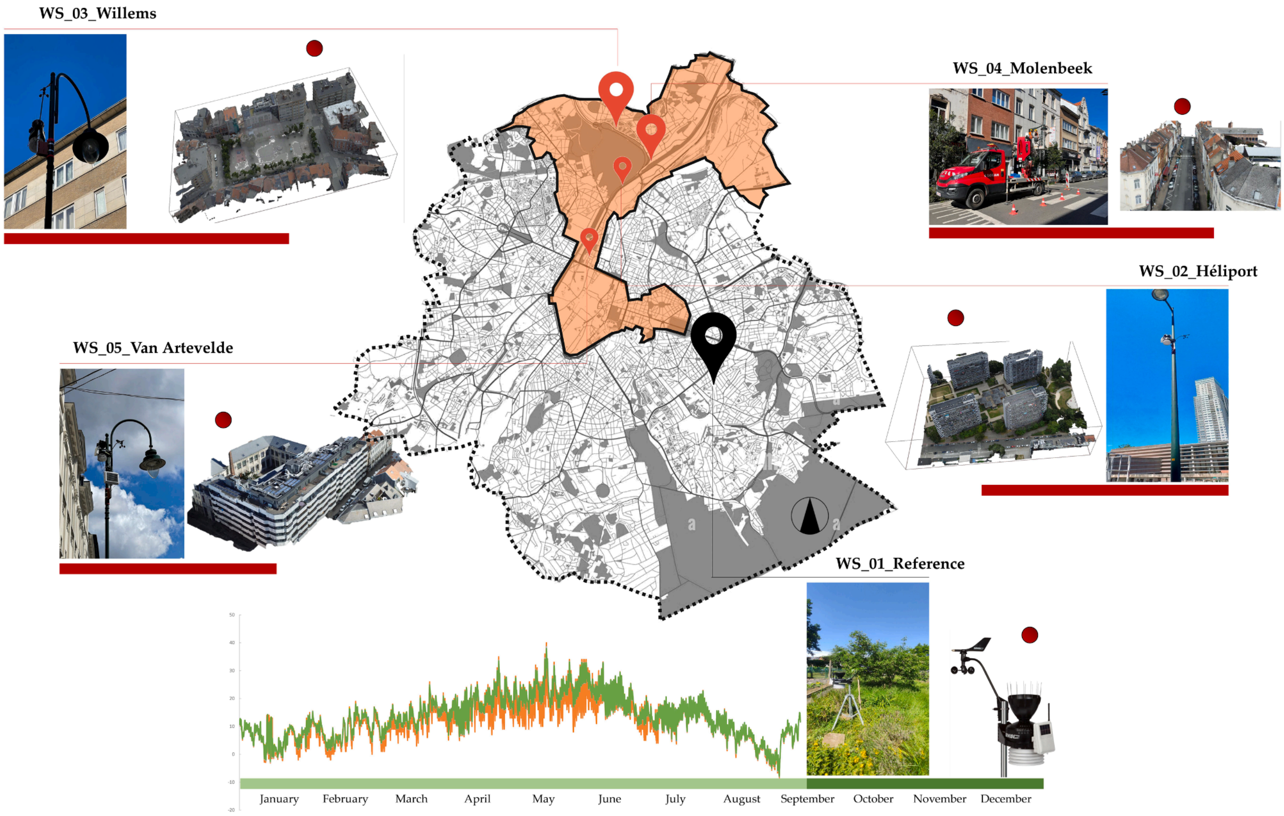


Fig. 2. Map of Brussels Capital Region and locations of weather stations. The orange color represents the Brussels commune study area, which includes the four urban sites.

temperature of 25°C or higher, during which at least 3 (three) must reach a tropical temperature of 30°C or above (Ahmed et al., 2023). In fact, during the summer of 2006 the Netherlands experienced a severe heat wave that lasted 16 days. However, the hottest wave occurred in July 2019, with a maximum temperature of 37.5°C over six days. Based on these definitions, a heat wave is a period of at least five consecutive days with a maximum temperature exceeding 25°C, during which at least three days have a maximum temperature exceeding 30°C (Van den Wyngaert et al., 2021). Overall, heat waves differ in three main aspects: (i) temperature metric; (ii) intensity, which means the temperature threshold; and (iii) duration (Xu et al., 2016). In this regard, studies have used maximum, average, apparent temperatures, and heat index as

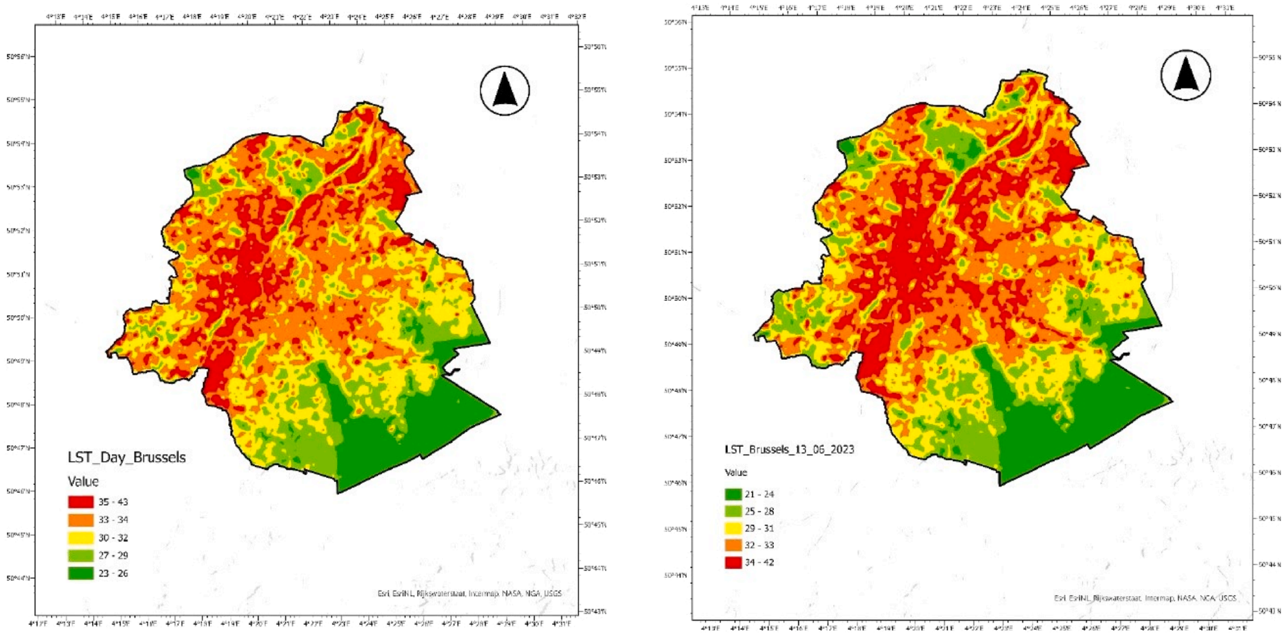


Fig. 3. Comparative mapping of the recorded heat waves during August 2022 and June 2023 in the Brussels Capital Region. Maps are based on Land Surface Temperature (LST) data obtained via Landsat 8.

measures of heat wave magnitude. Furthermore, the intensity has been investigated using two types of temperature thresholds: temperature percentiles or absolute thresholds. Most prior studies used maximum temperature as a temperature indicator and adopted an absolute threshold, whereas those using mean temperature typically used a relative threshold. Regarding duration, prior studies defined the heat wave as heat episodes lasting several days, ranging from 1 to 7 days. As shown in Fig. 3, the comparison of heat wave magnitudes and affected areas across the Brussels Capital Region between the recoded heat wave of August 2022 and June 2023 was clear, indicating that heat wave episodes have occurred earlier, longer, and more frequently over recent years.

2.3. Urban heat island (UHI) characterization

To characterize the urban heat island (UHI) effects during summer overheating in the Brussels Capital Region, five representative locations were selected, ranging from urban sites close to the downtown neighbourhoods (Brussels commune) to suburban area. Similarly to numerous studies, the UHI intensity was calculated based on air temperature differences between urban and rural/suburban areas, expressed as: UHI intensity = $T_{\text{urban area}}$ - $T_{\text{rural area}}$ (Ahmed et al., 2025, Sayad et al., 2023). As is widely known, $T_{\text{urban area}}$ is air temperature measured within the built-up area, while the $T_{\text{rural area}}$ is from a reference location outside the city, minimally affected by urbanization (Yuan et al., 2025).

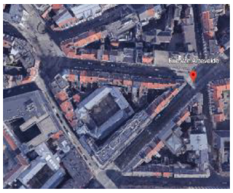
This study aimed to characterize near-surface UHI intensities and their impact on thermal comfort in Brussels during heat waves between July and September 2022.

Climate data for the five locations were collected through in-situ field measurements from five weather stations (WS) installed at the selected sites: WS_01, WS_02, WS_03, WS_04, and WS_05, as shown in Table 1. The monitoring network became operational on July 4, 2022, for all weather stations. The recorded data from the urban weather stations are compared with those from the reference weather station. The stations are Wireless Davis Vantage Pro 2 Plus (Fig. 2), equipped with main sensors: anemometer for wind speed and direction (accuracy ±0.5 (m/s)), air temperature (accuracy ±0.5°C) and relative humidity (accuracy ±3 %), solar radiation (accuracy ±5 %), UV radiation (accuracy ±5 %), and a rain collector. All the weather stations installed in urban locations are mounted on streetlamps at a height of 2.50 meters above the ground to avoid emissivity and radiation exchanges.

All the provided climate data are stored as 15-minute block averages

Table 02

Spatial characteristics and locations of the sites used in the study in Brussels (Attia et al., 2023).

Sites Weather stations		Location GPS	Aerial photo 2023	3D Drone shot	Spatial Characteristics	Major aspects of the sites
WS_01	**Uccle** Karrenberg 44, Watermael Boitsfort, 1170 Bruxelles	50.80° l.at 4.42° Lon		-	Build.Height: 7 m Build.Density: 0.30 Veg.Coverage: 0.50	• Low density • Large vegetated area including gardens and parks • Pavillion housing
WS_02	**Heliport** Avenue de l'Héliport, All. Verte 16, 1000 Bruxelles	50.86° Lat 4.35° Lon			Build.Height: 20.4 m Build.Density: 0.33 Veg.Coverage: 0.30	• Sparse • Neighbourhood dedicated to transport infrastructure • Urbanism of the open block
WS_03	**Willems** Rue de la Comtesse de Flandre 62, 1020 Bruxelles	50.87° Lat 4.35° Lon			Build.Height: 17.5 m Build.Density: 0.70 Veg.Coverage: 0.20	• Closed-block urban planning • Dense • Public space • Slightly vegetated
WS_04	**Molenbeek** Rue Marie-Christine 52, 1020 Bruxelles	50.87° Lat 4.36° Lon			Build.Height: 15 m Build.Density: 0.75 Veg.Coverage: 0.15	• Neighbourhood dedicated to transport infrastructure • Less vegetated area
WS_05	**Van Artevelde** Rue Van Artevelde 63, 1000 Bruxelles	50.84° Lat 4.34° Lon			Build.Height: 15 m Build.Density: 0.80 Veg.Coverage: 0.20	• Closed-block urban planning • Dense island • Slightly vegetated

Lat: Latitude; Lon: Longitude

on the WeatherLink Live cloud platform for the Davis Vantage Pro 2 Plus (Attia et al., 2023). In total, the recording reached 301007 data in each weather station, comprising 49 climatic parameters. Following prior studies relevant to the study purpose and to ensure the readability of the climate data results, we used hourly average and maximums for the principal parameters: air temperature (°C), relative humidity (%) and wind speed (m/s).

The study scope covered one suburban station, namely Uccle (S1), considered the reference station, and four residential areas: Heliport (S2), Willems (S3), Molenbeek (S4) and Van Artevelde (S5), as urban stations.

As a purely field measurement-based study, a comparison between the implemented weather stations and available satellite datasets (Visual Crossing Weather API, 2025) is presented in Appendix A solely to provide a general understanding of the differences between satellite and near-surface temperatures.

In fact, the selection of the conducted sites was carried out in collaboration with the Climate Unit of the Urban Planning Department of the Brussels commune (VBX). As the main location, the Uccle region is the principal site for meteorological measurements in the Capital. On the other hand, the chosen urban sites were selected based on specific spatial criteria: urban form, geometry, vegetation cover, distances from downtown, and socio-economic profiles (Table 02). Most of the selected sites contain squares, schools, markets, and mainly residential buildings. The Brussels commune (VBX) has considered these sites crucial zones and a priority for a citywide mitigation plan against the urban heat island effects. The initial selection comprised 10 zones, encompassing total of 29 districts. However, the selection was, and the choice is mainly related to the availability of weather stations and the need for urban arrangements at these sites.

2.4. UHI thermal mapping

The analysis of statistical series with GIS widely uses spatial interpolation methods. These techniques enable the creation of continuous data surfaces from a limited set of sampling points, as is often the case for climatic variables such as temperature or precipitation (Li and Heap, 2008). GIS software such as ArcGIS and QGIS, offer multiple spatial interpolation methods, including inverse distance weighting (IDW), kriging, splines, etc. (Childs, 2004, Goovaerts, 1997, Merwade et al., 2006).

Spatial interpolation is a process used for estimating surface values from a limited set of point data (Li and Heap, 2008). In this case, the input data consisted of air temperature measurements from all the weather stations across our study area. The goal of interpolation is then to convert these point data into raster data, where the study area is divided into a grid of cells, each assigned an interpolated value (Burrough et al., 2015, Willmott and Matsuura, 2006).

In the current study, the data processing was performed using ArcGIS 10.8 software. ArcGIS offers a wide range of spatial interpolation methods (Childs, 2004), which allows for the exploration of different approaches to accurately determine the near-surface UHI intensity within Brussels.

The objective is to map the air temperature differences between urban and suburban areas (Arnfield, 2003, Voogt and Oke, 2003). Thus, we used data from the four weather stations located at urban sites, which we compared with those from the reference station located in a suburban area (Uccle).

By calculating the differences for each period (day and night), we were able to highlight the areas most affected by the UHI. The interpolation methods in ArcGIS allowed converting these point differences into continuous surfaces, offering a fine-spatialized representation of UHI intensity at the scale of Brussels. To spatialize these temperature differences, we employed a hybrid approach that combines Multiple Linear Regression (MLR) and Inverse Distance Weighting (IDW) interpolation methods (Chai et al., 2011, Chang and Burningham, 2025, Zhang et al., 2024) to ensure a robust model. This approach is critical in spatial temperature analysis, especially when the number of measurement points is limited and the topography of the study area is complex.

MLR is known as one of the widely used models for identifying key variables that govern UHI intensities, and it can be used as a strong prediction tool (Oukawa et al., 2022). Further, the IDW technique assigns a smoothed value to each output grid cell by calculating it as a weighted average of the surrounding measurement points (Lu and Wong, 2008, Shukla et al., 2020). The weighting is inversely proportional to the distance, meaning the influence of a point decreases with increasing distance from the interpolated grid node. For our application, the hybrid approach MLR-IDW (Zhang et al., 2024) provides an effective balance between implementation simplicity and interpolation quality, despite being less sophisticated than geostatistical methods, such as kriging (Li and Heap, 2008). Moreover, this method enhances accuracy by integrating the strengths of two analytical techniques. First, multiple regression analysis incorporates multiple explanatory variables that affect the temperature pattern. Second, inverse distance weighting spatial interpolation corrects for localized temperature variations that remain unexplained by the overall regression model. Key parameters such as the number of data points and the weighting factor have been iteratively adjusted to optimize the interpolation accuracy. Additionally, altitude was considered an explanatory variable with a high correlation to temperature.

2.5. Humidex index

Humidex is an index number used to describe the perceived thermal feeling of a person by combining the effects of heat and humidity. Many studies consider temperature and relative humidity are the best predictors of potentially lethal weather conditions, which aligns with human thermal physiology, as both variables influence body heat exchange (Mora et al., 2017). This relationship explains why these variables are incorporated into traditional thermal indices such as the Humidex index. Humidex thus combines temperature and humidity into a single index value that represents the temperature perceived, and consequently, a measure of thermal discomfort. As it considers the two most important factors that affect summer comfort, it is a better method of measuring how stifling the air feels, more than either temperature or humidity alone (Orosa et al., 2014). Consequently, Humidex is widely used to determine the thermal environment impacted by UHI effects and heat waves during the summer season.

For calculation, we employ mathematical equations (see Eq. (1) and Eq. (2)) which incorporate relative humidity and air temperature as main variables (T = Air temperature (°C), H = Relative humidity (%), e = water vapor pressure (mb)) (Masitoh and Rusydi, 2020, Rana et al., 2013).

$$\text{Humidex} = T + \frac{5}{9}(e - 10) \qquad \text{(Eq. (1))}$$

$$e = 6.112 \times 10^{\left(\frac{7.5T}{237.7+T}\right)} \times \frac{H}{100} \qquad \text{(Eq. (2))}$$

Table 3
Humidex index ranges and bioclimatic thresholds (Masitoh and Rusydi, 2020).

Humidex (H) ranges	Bioclimatic condition	Bioclimatic comfort/discomfort
$H < 27$	Comfort	Bioclimatic comfort
$27 < H < 30$	Little discomfort	Bioclimatic discomfort due to overheating
$30 < H < 40$	Discomfort	
$40 < H < 45$	Great discomfort	
$45 < H < 54$	Dangerous	
$H > 54$	Heat stroke imminent	

The Humidex ranges related to bioclimatic conditions and bioclimatic comfort/discomfort are described in Table 03. Bioclimatic comfort/discomfort refers to the sensation of thermal conditions experienced by the human body (Ahmed et al., 2023).

3. Results

The measurements were taken between July 5, 2022, and September 5, 2022 at five different sites within the Brussels Capital Region, specifically the Brussels commune and Uccle areas. Figs. 4 and 5 show the air temperature variations during the study period and the three major heat waves (HW) recorded in July and August. The current study focuses on maximum and averages temperatures to characterize the near-surface UHIs.

Despite the different geometries of the conducted sites: (S2, S3, S4, and S5), the hourly temperature averages obtained at the sites revealed a close similarity in daytime and nighttime hours (Fig. 4). Furthermore, the daytime and nighttime hours were determined based on the sunrise and sunset times in Brussels during the studied months, with daytime hours from 05:00 to 20:00 and nighttime hours from 21:00 to 04:00.

As shown in Fig. 4, the box plots showed similar measured temperature distributions within the range of 13°C to 39°C across the four urban sites, whereas the suburban site showed a range of 8°C to 40°C. Moreover, the median and interquartile (IQR = Q3 - Q1) values varied among sites as follows: 20°C in Uccle (S1) with IQR = 7°C, 21°C in Heliport (S2) and Willems (S3) with IQR = 5°C, 22°C in Molenbeek (S4) and Van Artevelde (S5) with IQR = 6°C, respectively. Further, the median values for (S1), (S2), and (S3) remain below 25 % of their respective interquartile mean ranges.

Overall, the maximum temperature recorded (T_{max}) during the study period across all urban sites was 39°C. In contrast, the suburban site (Uccle) reached 40°C due to its greater solar exposure compared to urban areas. Otherwise, the maximum temperatures occurred at different times and dates across the stations. For example, stations S2, S3, and S4 recorded their peaks between 17:00 and 18:00, while station S5 reached its maximum at 11:00 on July 19. On the other hand, S1 shows its maximum temperatures between 14:00 and 15:00 on July 18. These maximum values were recorded during the heat wave days across several successive hours of the day.(Fig. 5).

Further, the minimum temperature (T_{min}) recorded at the urban sites S2, S3, S4, and S5 was 13°C from 05:00 to 07:00 in July, whereas the minimum at the suburban station S1 was 8°C at 05:00 obtained in August.

Therefore, the diurnal temperature ranges varied from 18°C to 29°C across all monitoring sites, with an overall daily average of 22°C. These average temperatures fluctuated in response to successive heat wave events and natural variations between daytime and nighttime periods (Table 4). Accordingly, the heat waves significantly influenced both the intensity and duration of overheating hours.

In fact, the study used the average temperature as a relative threshold to define heat wave intensity. Upon first reading, the first heat wave period (HW_1) was the longest heat duration of the year, lasting 09 consecutive days from July 12 to July 20. It showed the highest and uniform temperature elevations across all sites, with intensity reaching 40°C. The second heat wave (HW_2) lasted 07 consecutive days from July 28 to August 3, with a lower intensity than the precedent reaching 35°C, The latest heat wave (HW_3) occurred from August 09 to August 15, lasting 07 consecutive days with similar intensity to the second, reaching 35°C, lasted 07 consecutive days indicating similar temperatures from August 09 to August 15 (Fig. 6).

During the summer season, the frequency of HW episodes increases in areas with high levels of built-up density, and UHI intensities further amplify this effect.

Therefore, the intensity of the HWs was apparently higher at nighttime than during the day, with HW_1 and HW_3 showing the highest intensities, ranging from 5°C to 6°C across urban sites. On the other hand, the temperature differences (Δ) between heat waves and climatological averages were evident, ranging from +1°C to +2°C above normal (Table 04).

The diurnal UHI intensities across all sites had the following temporal distribution: (i) 2 % of the total studied period showed an effect of UHI lasting less than five hours per day; (ii) 19 % of the total period had UHI effect lasting between 5 and 10 hours per day; (iii) 60 % of the total period had UHI effect lasting between 10 and 15 hours per day; (iv) 07 % had UHI effect lasting among 15 to 20 hours per day; (v) and 12 % had UHI effect lasting above 20 hours during a day. This breakdown provides insights regarding the frequency and magnitude of the UHI effect in the studied area. These differences are analyzed for both nighttime (UHI_N) and daytime (UHI_D) hours in Figure 7 and Table 5.

As reported in Fig. 7, results showed distinct temperature differences between suburban and urban areas, reaching 19°C at nighttime and 20°C during the daytime. Specifically, UHI_N ranged from -2°C to 18°C, -3°C to 19°C, -2°C to 19°C, and -5°C to 16°C in (S2), (S2), (S3), and (S4), respectively. Moreover, UHI_D values ranged from -12°C to 20°C, -11°C to 20°C, and -12°C to 19°C in (S1) and (S2), (S3), and (S4), respectively. On the other hand, the interquartile range (IQR) varied from 3°C to 5°C during nighttime and from 6°C to 9°C during daytime hours. Otherwise, the maximums, minimums, and averages of the near-surface UHI diurnal ranges were reported in Table 5.

Interestingly, the summer period exhibited exceptionally high daily UHI intensities, with the most significant values recorded during July across all conducted sites. Maximum nighttime UHI intensities UHI_N_{max} (July) reached 19°Cat both Willems (S3) and Molenbeek (S4), while Heliport (S2) and Van Artevelde (S5) recorded maximum values of 18°C and 14°C, respectively. On the other hand, daytime maximum intensities UHI_D_{max} reached 20°C in S2, S3, and S4, and 19°C in S5. Moreover, August showed slightly higher intensities than July during the nighttime and daytime hours. Accordingly, nighttime maximum intensities UHI_N_{max} (August) reached 12°C in S2, and S3, 13°C in S4, and 16°C in S5, respectively. During the daytime, the maximum intensities UHI_D_{max} was 11°C within S2, S3, and S4, and 18°C in S5, respectively.

In September, the maximum intensities decreased over nighttime and daytime hours, with UHI_N_{max} varying between 5°C and 7°C, versus UHI_D_{max} between 5°C and 6°C in max.

Otherwise, the UHI daily averages varied from 3°C to 5°C throughout all sites during nighttime hours, whereas the diurnal averages of UHI intensities balanced between -1°C and 1°C, across urban stations (S2, S3, S4, and S5).

According to previous results, the maximums of UHI intensities were recorded during the heat waves (HW) periods, which increased the UHI intensity's difference between normal climatological summer days and overheating days to +2°C at nighttime and +1°C during daytime hours.

The daily minimum UHI intensities, UHI_{min} were clearly observed during daytime hours, highlighting the more rapid elevation of temperatures in suburban areas than urban areas throughout the day. Given the deeper analysis regarding this difference, the decrease of temperatures through urban sites is due to Urban Cool Island (UCI) effect, a phenomenon noted during daytime hours and strongly perceived on heat wave days. Fig. 8 shows the near-surface UHI intensity variations from July to September 2022.

In fact, July daytime minimums UHI_D_{min} (July) reached values of -12°C in S2, S3, and S5, and -11°C in S4, respectively. Furthermore, the daytime minimums UHI_D_{min} (August) at suburban and urban sites were -7°C in S4, -9°C in S2, and S3, and -11°C in S5, respectively. Although September revealed the lowest daytime minimum UHI_D_{min} (September) of UHI intensities during the conducted period, at -6°C in S5, and -7°C in S2, S3, and S4, respectively.

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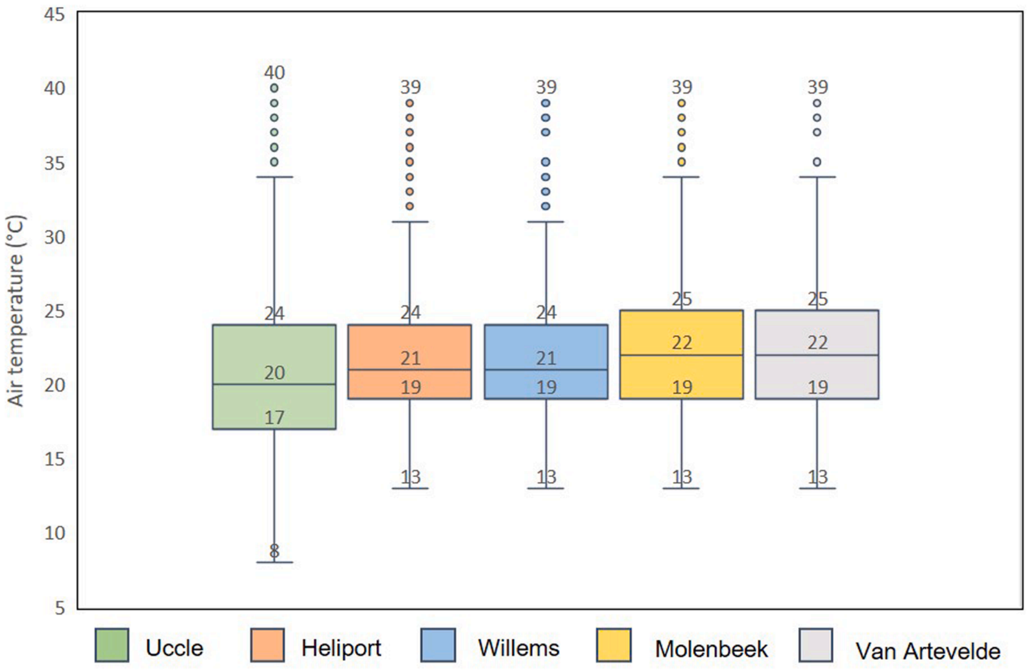

Fig. 4. Box plots of air temperature throughout the conducted sites representing maximums, minimums, and median values.

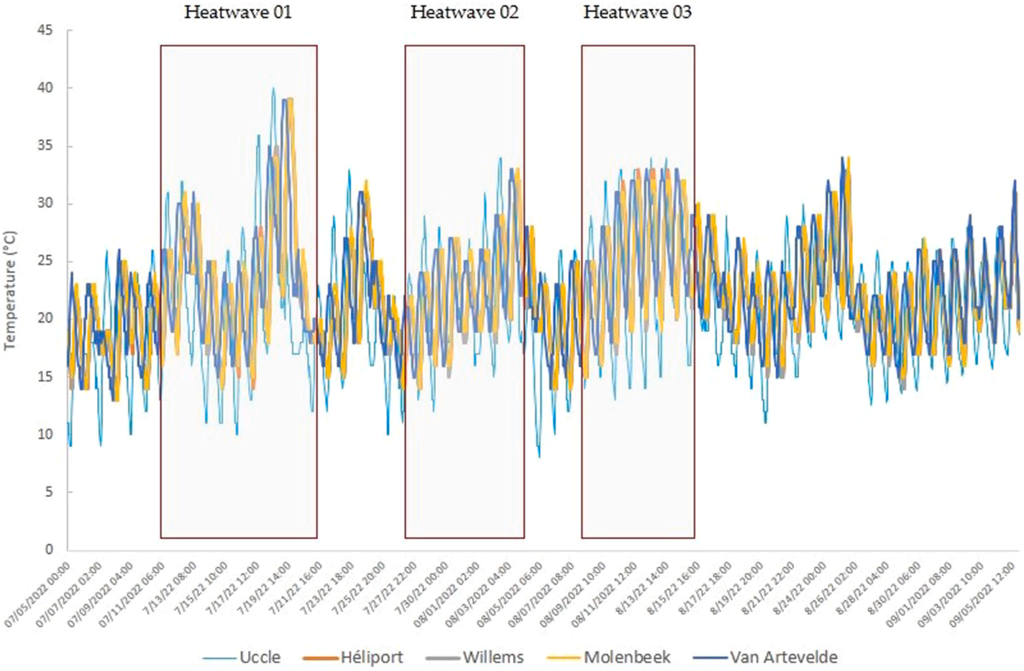

Fig. 5. Air temperature fluctuations and heat wave episodes between July and September 2022 within all the implemented weather stations in the Brussels area.

As previously reported, UHI intensities showed significantly greater sensitivity to nighttime heat wave periods than to daytime hours. Across all three heat wave events HW_1, HW_2, and HW_3, the average UHI intensity between urban and suburban areas was consistently higher at night than during the day. While urban impervious surfaces absorb substantial solar energy during daytime hours, the interaction between heat waves and UHI intensities primarily occurs at night, with heat waves exerting a more pronounced impact on nighttime temperatures than on daytime ones.

Fig. 9 and B (appendix) present thermal maps of the Brussels Capital Region for July, August and September, revealing significant spatial variations in near-surface UHI intensity and monthly average temperatures. In July, the highest nighttime temperatures (averaging 20.3°C to 20.6°C) were observed in the central and northwestern areas, specifically around Heliport (S2), Willems (S3), and Molenbeek (S4). Moderately high averages (18.8°C to 20.2°C) were observed surrounding Van Artevelde (S5). The southeastern part of Brussels, particularly around Uccle, showed the lowest temperatures (16.2°C to 17.4°C), likely due to extensive green spaces and lower urban density. August showed a slight increase in average nighttime temperatures compared to July averages. The maximum range was (21.6°C to 21.8°C), occurring in the same areas that experienced the highest temperatures in July. The minimum range

Table 4
Intensity of near-surface UHI (difference between urban sites and suburban site) during night and day observed during climatological and heat wave days.

UHI $_{intensities}$ (°C)	Hours	Heliport	Willems	Molenbeek	Van Artevelde
Climatological	Nighttime	4.0	4.0	5.0	4.0
HW $_1$		6.0	6.0	6.0	5.0
HW $_2$		4.0	4.0	4.0	3.0
HW $_3$		6.0	6.0	6.0	5.0
Δ_1		2.0	2.0	1.0	1.0
Δ_2		0.0	0.0	- 1.0	- 1.0
Δ_3		2.0	2.0	1.0	1.0
Climatological	Daytime	- 1.0	0.0	0.0	1.0
HW $_1$		0.0	0.0	1.0	2.0
HW $_2$		- 1.0	- 1.0	0.0	1.0
HW $_3$		0.0	0.0	1.0	2.0
Δ_1		1.0	0.0	1.0	1.0
Δ_2		0.0	- 1.0	0.0	0.0
Δ_3		1.0	0.0	1.0	1.0

was (17.1°C to 18.2°C) at the same area that had the lowest temperatures during July. Otherwise, during September, the minimum averages were (17°C to 18.7°C) around Uccle, while the warmest area was concentrated around Van Artevelde (S5) with a range (21.7°C to 22°C), surprisingly higher than July and August monthly averages. Other urban areas varied between 20.4°C to 21°C.

According to the analysis of Humidex index analysis in Fig. 10, the thermal environment inside Brussels' study area was acceptable during the study-period. However, there are several periods (hours and days) during which thermal discomfort was observed at the five sites.

During 1511 measured hours, the comfort zone presented durations of 72 %, 71 %, 69 %, 67 %, and 62 %, corresponding to 1089, 1083, 1041, 1010, and 943 hours throughout S2, S3, S1, S4, and S5, respectively. Despite these comfortable zones, the thermal discomfort hours were significant and slightly longer than Brussels' climate conditions. The increase in temperatures generated multiple thermal stress perceptions, such as little discomfort with a range of 14 % to 18 % equal to 209 and 276 hours, where S4 was the most affected site. The discomfort period presented a range of 11 % to 20 % equal to 296 and 250 hours, where S5 was the most affected site. In addition, a significant discomfort period was observed through S1 and S5, lasting 21 and 38 hours, respectively. Remarkably, S5 revealed a 14-hour period of high thermal activity during the conducted period, which can significantly affect human health and activities.

Surprisingly, the Humidex fluctuations are weakly related to UHI intensities at nighttime or daytime hours but correspond to the HW levels specifically under the afternoon solar radiation intensity from 14:00 to 16:00.

Accordingly, Van Artevelde (S5) identified the warmest site among the other sites. The suburban station (S1) experienced significant solar exposure time, which can rapidly affect the site's thermal levels.

Climatic variables between July and September 2022 were investigated. Statistical analysis of UHI intensities, relative humidity, and Humidex index is shown in Table 06. All summer months showed a significant difference ($p < 0.05$) in UHI intensities between the urban sites: S2, S3, S4, and S5, and the suburban site S1 (Table 7). Air temperature averages varied between: 20.8°C in Uccle (S1), 21.9°C in Heliport (S2) and Willems (S3), compared to 22.4°C and 22.6°C in Molenbeek (S4) and Van Artevelde (S5), respectively.

Furthermore, relative humidity differences inside urban sites versus the suburban site were significant ($p < 0.05$), whereas the averages achieved were: 65 % in S1, 57 % in S2 and S3, 56 % in S4, and 55 % in S5.

Additionally, the Humidex index values showed significant differences ($p < 0.05$) between urban sites and rural sites during the conducted study-period. Humidex index averages were 24°C in Uccle (S1), Heliport (S2) and Willems (S3), 25°C, 26°C in Molenbeek (S4) and Van Artevelde (S5), respectively. Monthly averages ranges were 23°C, 24°C, 25°C during July; 25°C, 26°C, and 27°C during August; 24°C, 25°C, and 26°C during September.

5. Discussion

This section presents the primary recommendations, strengths and limitations, and implications for practice and future work based on the research findings.

This to characterize the UHI intensities using a data-driven approach across urban and suburban sites in Brussels.

This study investigated the UHI spatial-temporal effects on outdoor thermal comfort. Similar to the study by Hamdi et al., 2016 (Hamdi et al., 2016) in Brussels, the nighttime UHI is enhanced under HW conditions compared to climatological conditions. Current results revealed more significant UHI effects, with 2/3 of the total period experiencing elevated temperatures in urban areas, reaching 20 hours per day during heat wave periods. During July, distinctive patterns of UHI intensity variations became apparent, with particularly pronounced differences between nighttime and daytime effects. The most striking observation was the nighttime UHI intensity which reached 19°C, representing the peak temperature differential between urban and suburban areas throughout the study period. These extreme nighttime temperature differences significantly exceed the UHI intensities previously reported by Hamdi et al., 2016 (Hamdi et al., 2016) for the same study context, indicating an intensification of the UHI effect in recent years. Consequently, heat wave periods serve as significant amplifiers of UHI intensity, creating more severe thermal conditions in urban environments than previously observed in the Brussels Capital Region.

Furthermore, in the research conducted by Lauwaet et al., 2016 (Lauwaet et al., 2016), based on numerical modeling prediction and simulation processing, the magnitude of Brussels UHI is not expected to change a lot in the near future, when presence of the UHI does have an impact on extreme temperatures, especially during nighttime hours, and UHI effects are expected to occur more frequently in the future. Although this study does not consider future urban growth in Brussels, the city is expected to face an increased risk of extreme heat events due to climate change. This climate-related risk is further exacerbated by the current extent of urbanization in the Brussels Capital Region.

In a different context and from another perspective, Fahy et al., 2025 found, in their recent study evaluating thermal comfort and combining remote sensing and field measurements, that LST is a misleading indicator of thermal discomfort in cities (Fahy et al., 2025). The research showed that LST captures rooftop heat, not street-level conditions where people actually live, move, and suffer. Accordingly, near-surface observations can be the most accurate method for representing the actual UHI intensities within urban areas.

5.1. Summary and main findings

At the canopy level, the UHI effect was clearly observed in the studied areas, with variations over a 60-day period. The distribution of daily UHI intensity showed that a significant proposition of the studied period (67 %) experienced distinct UHI effects lasting between 10-20 hours per day, indicating a substantial impact on the local climate.

Furthermore, distinct variations were observed in nighttime UHI intensities nighttime (UHI_N) and daytime (UHI_D) hours. Globally, UHI maximum intensities were closer during the nighttime and daytime hours, reaching up to 19°C in some urban sites, particularly during July. Otherwise, the daytime maximum intensities were slightly higher, ranging from 19°C to 20°C across the studied urban sites and the suburban site.

The UHI intensities had temporal variations, with July and August experiencing higher intensities compared to September. This variation aligns with the expected seasonal temperature variations, as the summer months are typically warmer.

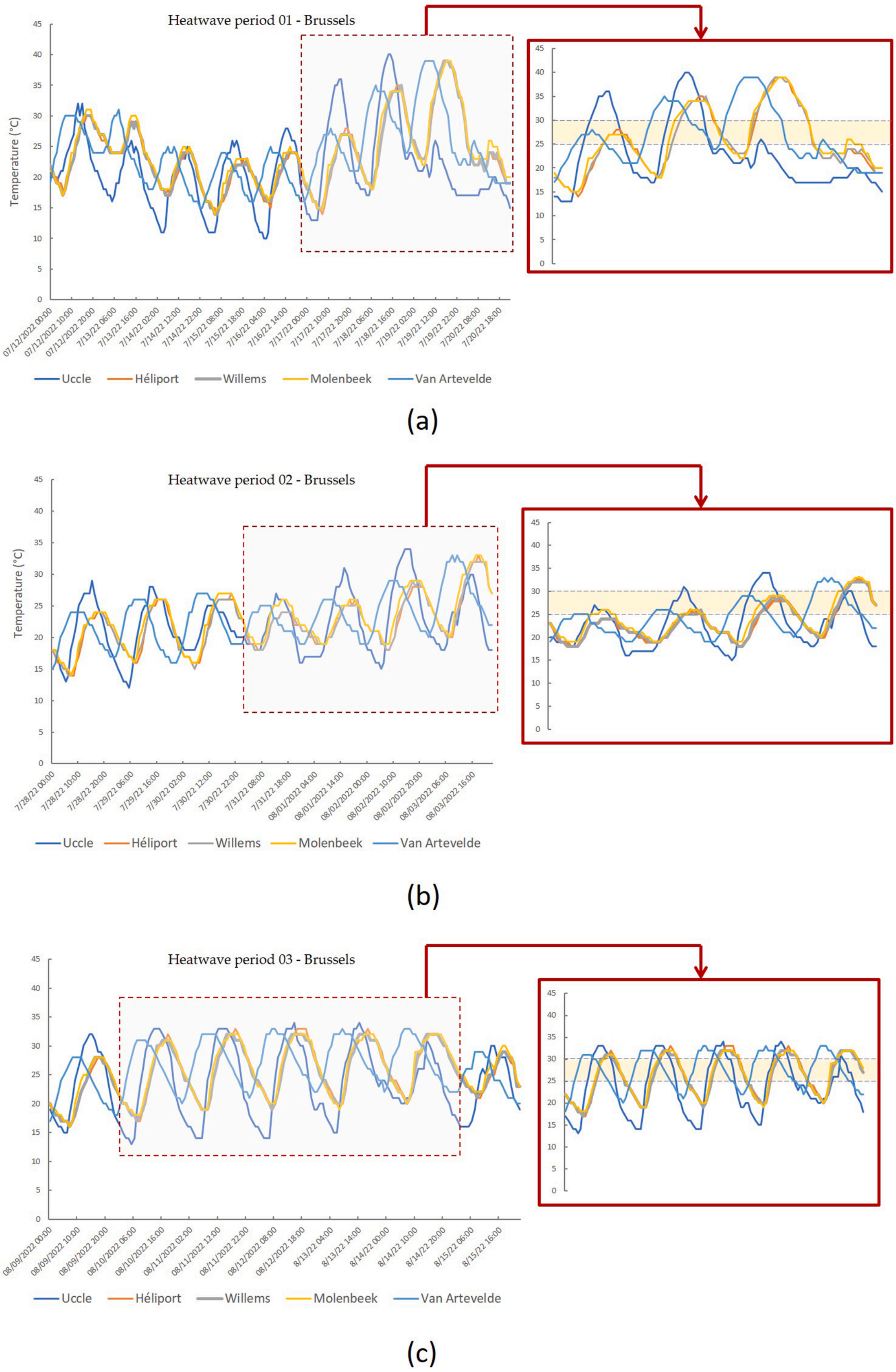

Fig. 6. Heat waves' episodes and magnitudes between July and September 2022 in the study area. (a) HW_1 lasted 09 days (12-20 July); (b) HW_2 lasted 07 days (July 28-August 03); (c) HW_3 lasted 07 days (09-15 August2022).[3].

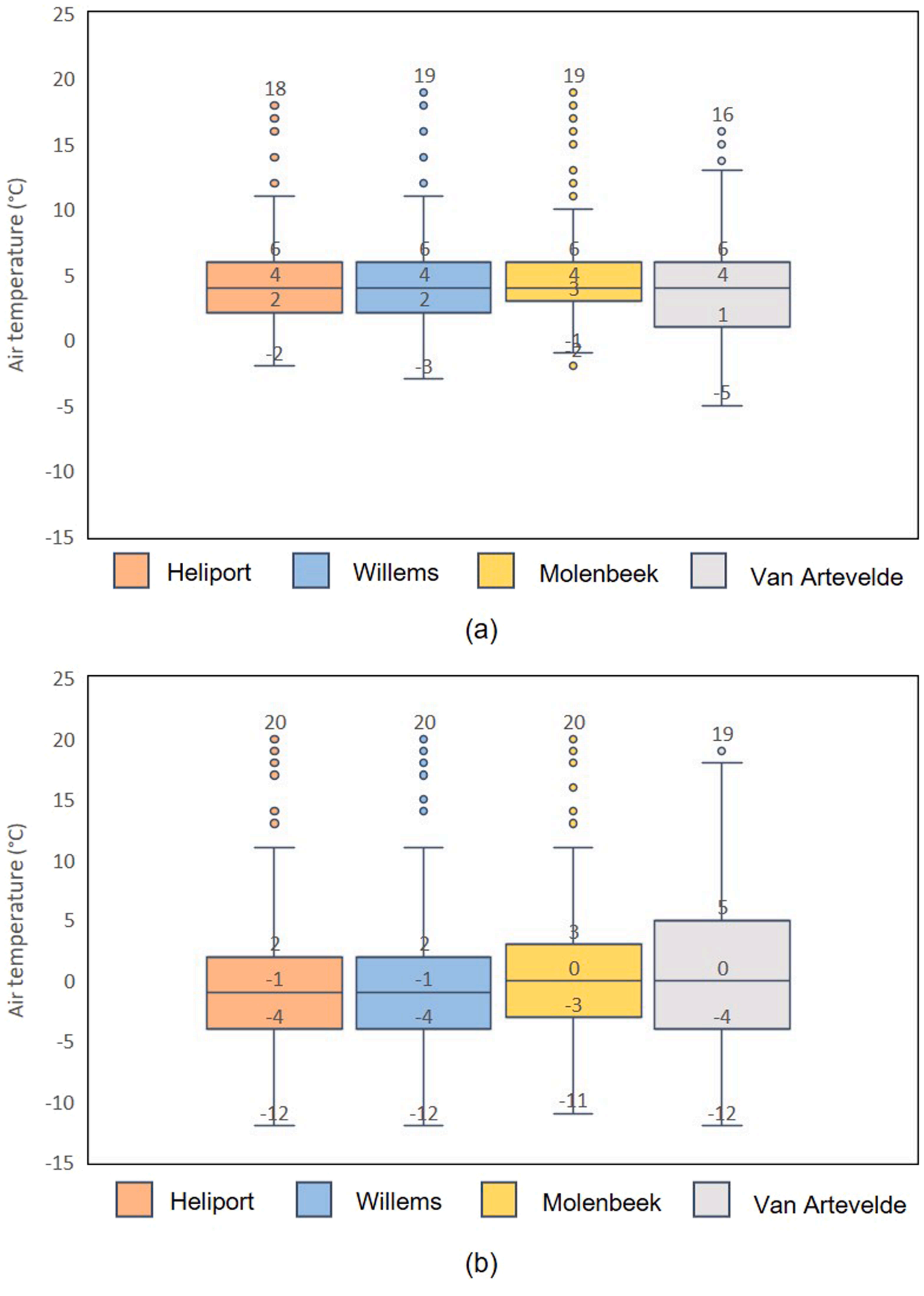

Fig. 7. Box plots of near-surface UHI nighttime and daytime hours intensities within urban sites: (a) UHI intensity at nighttime hours (UHI_N); (b) UHI intensity at daytime hours (UHI_D).

Interestingly, UHI intensities were found to be amplified during heat wave periods, with increases of up to 2°C at nighttime intensities and 1°C during the day compared to normal climatological summer days. This finding highlights that heat waves substantially worsen UHI intensity, creating a compounding impact on urban thermal environments.

On the other hand, the study identified the presence of an Urban Cool Island (UCI) effect during daytime hours, particularly during heat waves. This phenomenon, characterized by lower temperatures in urban areas compared to suburban areas, was observed across all urban sites studied, with diurnal minimum UHI intensities reaching a difference of -12°C at specific times.

Furthermore, the analysis based on the Humidex index revealed that the thermal environment in Brussels was acceptable during the study period, with a comfort zone being the most frequently observed across all sites (62 % to 72 % of measured hours).

However, there were still significant periods of thermal discomfort, ranging from little discomfort (14 % to 18 % of hours) to a discomfort range (11 % to 20 % of hours). Some sites even experienced significant discomfort (up to 38 hours) and hazardous thermal ranges (14 hours at

Table 5
Observed Maximums, minimums, and averages of near-surface UHI intensities (differences between urban sites and suburban site) during night and day from July to September 2022.

Month	Hours	UHI $_{\text{intensities}}$ (°C)	Sites			
			Héliport	Willems	Molenbeek	Van Artevelde
July $_{2022}$	Nighttime	Max	18	19	19	14
		Min	- 2	- 3	- 2	- 5
		Average	4	4	5	3
	Daytime	Max	20	20	20	19
		Min	- 12	- 12	- 11	- 12
		Average	- 1	0	0	1
August 2022	Nighttime	Max	12	12	13	16
		Min	0	0	0	- 5
		Average	4	4	5	4
	Daytime	Max	11	11	11	18
		Min	- 9	- 9	- 7	- 11
		Average	- 1	- 1	0	1
September 2022	Nighttime	Max	5	6	6	7
		Min	0	0	1	1
		Average	4	4	4	5
	Daytime	Max	6	5	6	6
		Min	- 7	- 7	- 7	- 6
		Average	0	0	0	0

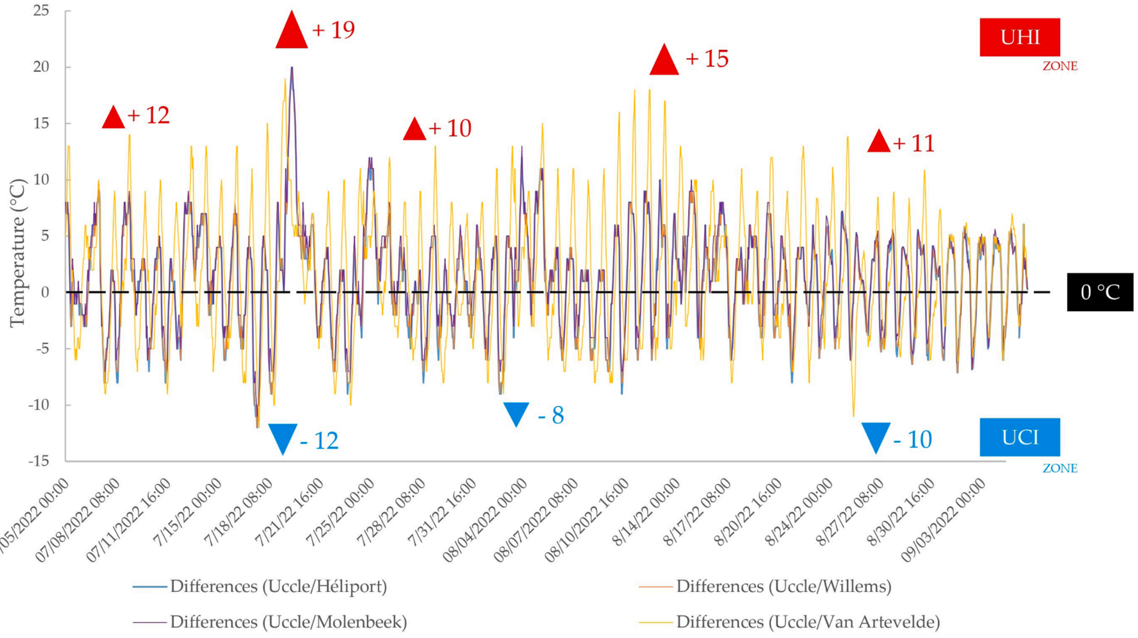

Fig. 8. Near-surface UHI intensity variations from July to September 2022 in Brussels.

the Van Artevelde site), which can negatively impact human health and activities.

The fluctuations in Humidex values were not strongly affected by UHI patterns during the day or night. Still, they were more influenced by heat wave occurrences and clearly elevated in the afternoon insolation, specifically between 14:00 and 16:00.

Remarkably, Van Artevelde (S5) was identified as the warmest among the studied locations. Interestingly, the suburban station (S1) was highly exposed to solar radiation, which can rapidly increase thermal stress levels, especially during heat wave periods.

These findings provide valuable insights into the spatial and temporal dynamics of the UHI and UCI effects in the studied area, highlighting the complex interplay between urban environments and local climate conditions. The observed patterns highlight the importance of considering these phenomena in urban planning and climate adaptation strategies to mitigate their impacts on human health and energy consumption.

5.2. *Strengths and limitations of this research*

Unlike many previous studies that investigated the UHI based on remote sensing and numerical modeling (Andrade et al., 2023, Lauwaet et al., 2016), the current paper's main strength lies in the characterization of the UHI effects based on a data-driven approach. The research performed accurate continued measurements throughout urban and suburban areas of Brussels, which determined alarming effects of the UHI during the summer.

Moreover, the study conducted a thorough analysis of the UHI effects by examining multiple metrics, including UHI intensity levels, nighttime and daytime variations, heat wave impacts, and outdoor thermal comfort within distinct sites. This multi-faceted approach provides a more holistic understanding of the phenomenon.

Furthermore, the spatial coverage of the study, which included measurements taken from five different sites, allowed for a comparison of thermal conditions across various urban and suburban locations. This

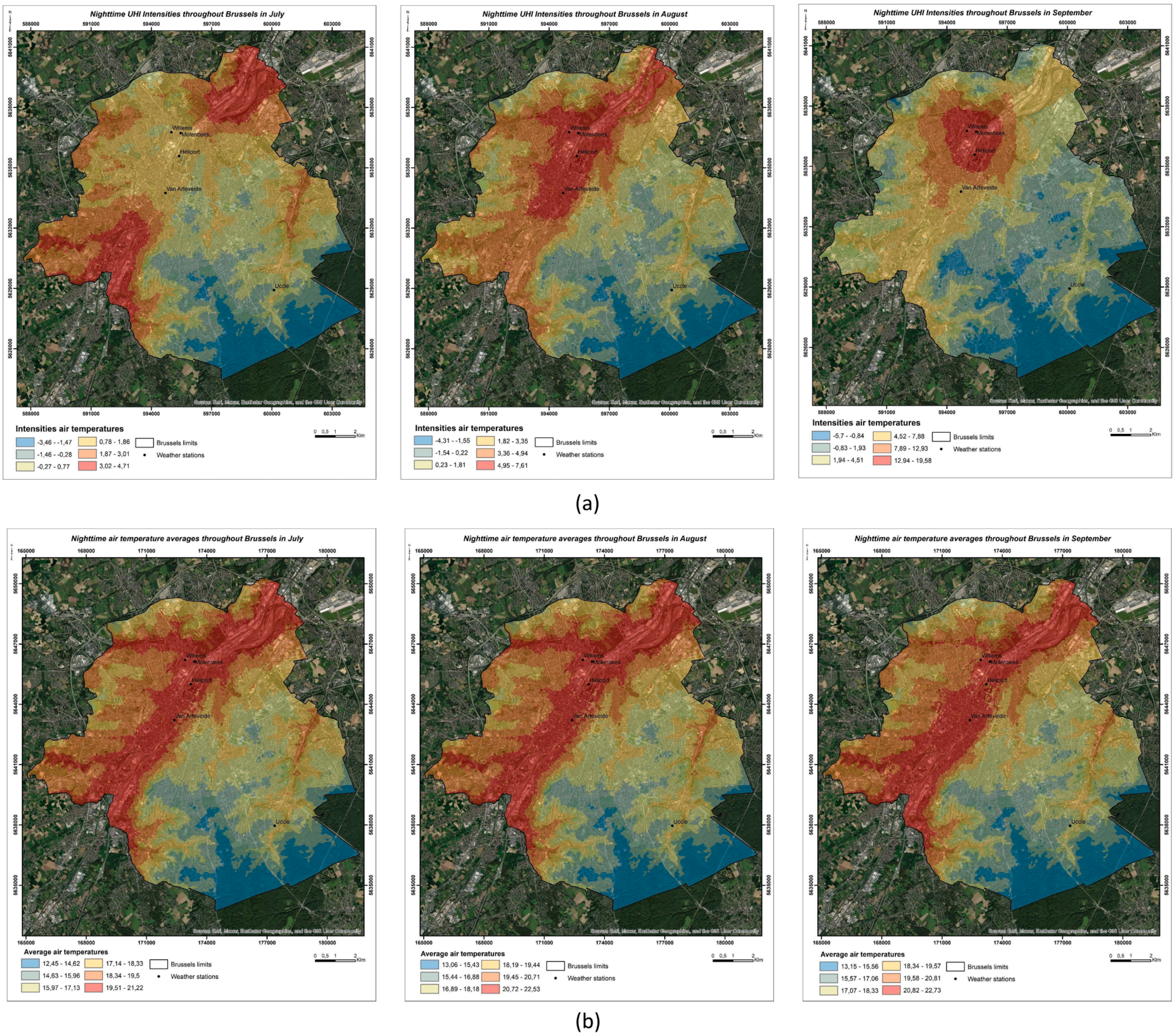

Fig. 9. Mapping of nighttime monthly UHI intensities and air temperature averages throughout Brussels from July to September 2022.

spatial diversity identified potential hotspots or site-specific patterns, particularly through the thermal mapping method.

The study analyzed data over an extended period, covering 60 days of the summer season. This temporal resolution enables the capture of variability and patterns associated with different seasonal conditions and weather events, such as heat waves.

The study did not focus solely on UHI effects but also assessed thermal comfort using the Humidex index. This approach provides valuable insights into the potential impacts on human comfort and health.

In addition to the UHI intensities, the study identified the occurrence of the Urban Cool Island (UCI) effect during daytime hours, particularly during the heat wave days. This finding highlights the complex interplay between urban environments and local climate conditions, thereby contributing to a more comprehensive understanding of the thermal dynamics in urban areas.

At the same time, the study has limitations. One of them is related to weather stations' and climate parameters. The study was limited by the lack of weather stations to cover a large area of the Brussels Capital Region and the necessary equipment to measure globe temperature, albedo, and air quality. Despite the acquisition of five weather stations, such as Davis Vantage Pro 2 Plus, the research still lacks an assessment of solar radiation effect which is considered as main factor in characterizing the UHI intensity and outdoor thermal levels. From September 2022 to February 2023, all weather stations encompassed unexpected storage issues at various times, resulting in the loss of substantial data and significantly limiting the study duration (Attia et al., 2023).

Additionally, the study does not perform a multi-factorial approach that considers the urban morphology and building finishes within local climate conditions (Heusinkveld et al., 2014, Van Hove et al., 2015). A combination of spatial and climatic characteristics enables the development of a comprehensive chart on the UHI effects and their temporal impacts, which can be standardized for UHI mitigation strategies in EU cities.

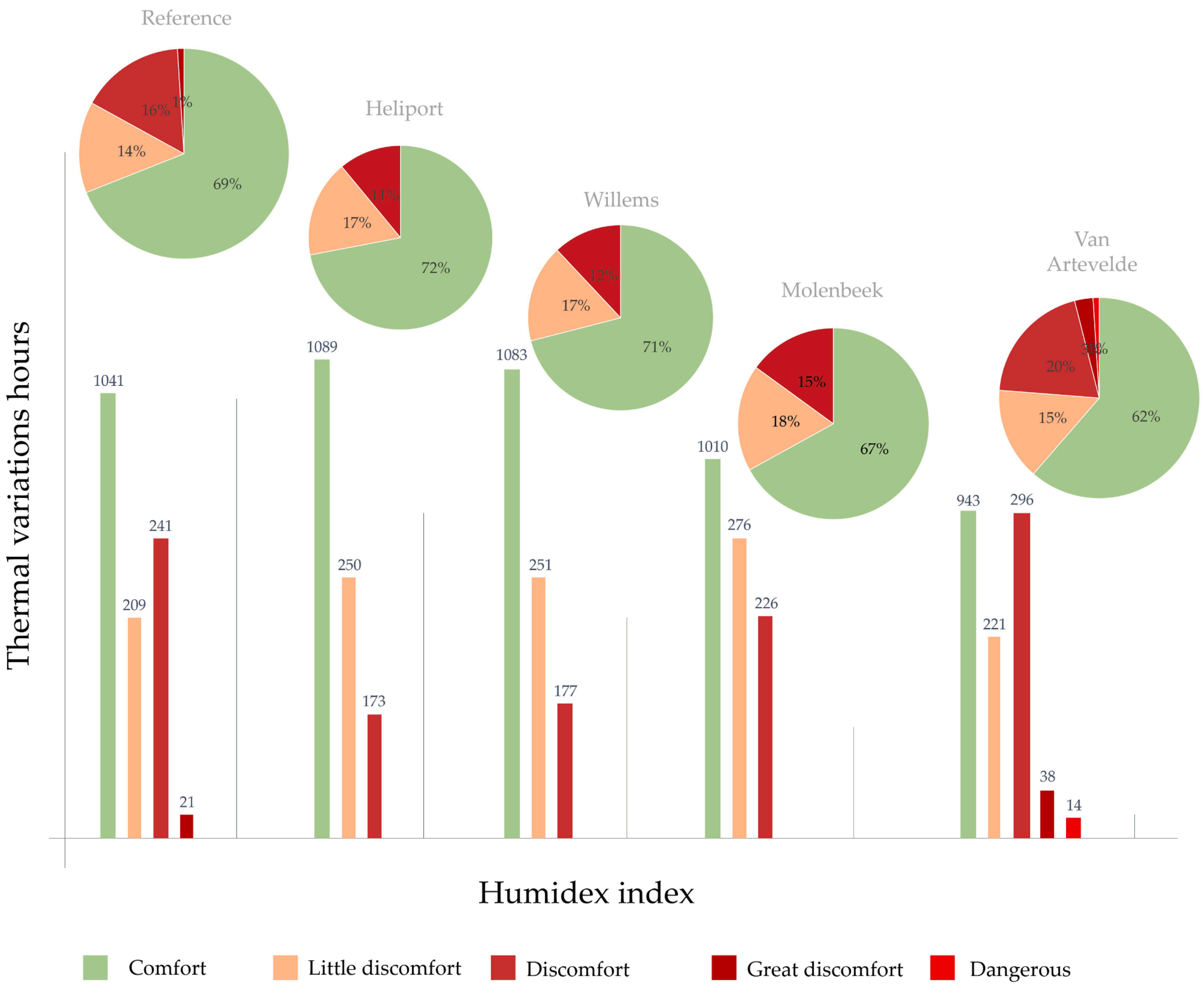

Fig. 10. Humidex index values throughout the Brussels study area.

Table 6
Correlation between air temperature, relative humidity, and UHI intensities with Humidex index (Pearson).

Parameter	Uccle	Heliport	Willems	Molenbeek	Van Artevelde
Air temperature (T_{air})	0.95	0.94	0.94	0.95	0.91
Relative Humidity (R_H)	-0.46	-0.58	-0.58	-0.58	0.20
Δ $T_{u\text{-}r}$	-	0.29	0.26	0.26	0.57

5.3. Future work and possible applications

The study's findings open the door to further research and practical applications to address the UHI effectively. Future research should expand spatial coverage by incorporating diverse urban morphologies and land-use patterns within Brussels. Integrating remote sensing techniques and numerical modeling can enhance understanding at a larger scale, enabling the creation of detailed thermal maps to identify hotspots for operational urban interventions.

The current paper presents part 1 of the research work. Part 2 of the study will utilize the collected data for numerical modeling and simulation using the Urban Weather Generator within the Grasshopper parametric software.

A targeted future objective will develop advanced algorithm links between real-time field measurements and satellite remote data, which can lead to predicting and generating thermal mapping based on microclimatic datasets and Land Surface Temperature (LST) via satellite.

Relationships between UHI mitigation strategies and other urban initiatives, such as implementing green infrastructure, should be explored. Investigating the role of urban design and materials in shaping UHI intensities can inform construction practices and effective building material choices to reduce heat absorption and enhance thermal comfort. The outcomes have potential applications in urban planning, public health, and energy management. Consequently, urban planners can

Table 7
Correlation between air temperature, relative humidity, and Humidex index differences in urban sites (p-value).

Parameters		Heliport	Willems	Molenbeek	Van Artevelde
p-value	UHI intensities (°C)	$p < 0.05$	$p < 0.05$	$p < 0.05$	$p < 0.05$
	Relative Humidity (%)	$p < 0.05$	$p < 0.05$	$p < 0.05$	$p < 0.05$
	Humidex index (°C)	$p < 0.05$	$p < 0.05$	$p < 0.05$	$p < 0.05$

follow the study findings to develop various mitigation strategies, such as cool roofs, vegetated areas, and optimizing urban ventilation corridors (Aboagye and Sharifi, 2024). In public health, identifying UHI hotspots and thermal discomfort zones can inform heat action plans and early warning systems to prevent heat-related risks (Ballester et al., 2023, De Troeyer et al., 2020).

The results can enhance energy management strategies by understanding the spatial and temporal patterns of UHI intensities, optimizing the distribution of cooling resources, and implementing demand-side management practices to reduce energy consumption and associated greenhouse gas emissions (Errebai et al., 2022, Salvati and Kolokotroni, 2023).

6. Conclusion

This study has made significant strides in advancing the understanding of UHI effects in Brussels during the summer season, offering a comprehensive methodology based on a data-driven approach.

The outcomes highlight the alarming effects of the UHI in Brussels, with distinct patterns observed between nighttime and daytime hours. The maximum UHI intensities were notably higher during nighttime, reaching up to 19°C in urban sites. This intense heat retention during the night can have significant implications for human health, indoor thermal comfort, and energy consumption, especially during heat wave periods.

Moreover, the study revealed that UHI intensities exhibit temporal variations that align with expected seasonal temperature changes, underscoring the exacerbating effect of heat waves, which amplify both nighttime and daytime UHI intensities by up to 2°C and 1°C, respectively. On the other hand, the study identified an Urban Cool Island (UCI) effect on heat wave days. This counterintuitive phenomenon, characterized by lower temperatures in urban areas compared to suburban areas, was observed across all studied sites, with daytime minimum UHI intensities reaching a difference of -12°C in some cases. This finding highlights the complex interplay between urban environments and local climate conditions, which can result in both heating and cooling effects.

Furthermore, the analysis based on Humidex showed significant periods of outdoor thermal discomfort, ranging from mild discomfort to dangerous levels. This emphasizes the potential impact of UHI on human health and well-being, underscoring the importance of mitigating these effects. In this light, the study findings have significant implications for urban planning and climate adaptation strategies in Brussels. By identifying UHI hotspots and thermal discomfort zones, urban planners can prioritize interventions such as increasing green spaces and implementing cool roofs. Specifically, these measures should target the '*Canopy plan 2020-2030*' and '*IBGE climate plan*' of Brussels, which focus on vegetation actions in response to climate change. Such measures help reduce the urban heat impact, enhance thermal comfort, and promote sustainable urban development. A heat action plan and early warning system can be developed to protect vulnerable populations during extreme heat events.

Future research should expand the spatial coverage of field measurements to encompass a broader range of urban morphologies and land-use patterns across Brussels. Additionally, integrating remote sensing techniques and numerical modeling can enhance understanding of UHI patterns at larger scales, enabling the creation of detailed thermal maps for the entire city.

Data availability

To download the technical report: https://hdl.handle.net/2268/303503

CRediT authorship contribution statement

Mohamed Elhadi Matallah: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Aissa Boulkaibet:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Formal analysis, Data curation. **Hicham Fawzi Arrar:** Writing – original draft, Software, Resources, Methodology, Data curation. **Tianyi Wang:** Writing – review & editing, Validation, Formal analysis, Data curation. **Deepak Amaripadath:** Writing – review & editing, Writing – original draft, Software, Methodology, Formal analysis. **Atef Ahriz:** Writing – review & editing, Writing – original draft, Validation, Resources, Methodology, Formal analysis, Conceptualization. **Mohamed Amer:** Writing – review & editing, Visualization, Validation, Software, Data curation. **Shady Attia:** Writing – review & editing, Validation, Supervision, Methodology, Conceptualization.

Declaration of competing interest

We wish to confirm that there are no known conflicts of interest associated with this publication, and there has been no significant financial support for this work that could have influenced its outcome.

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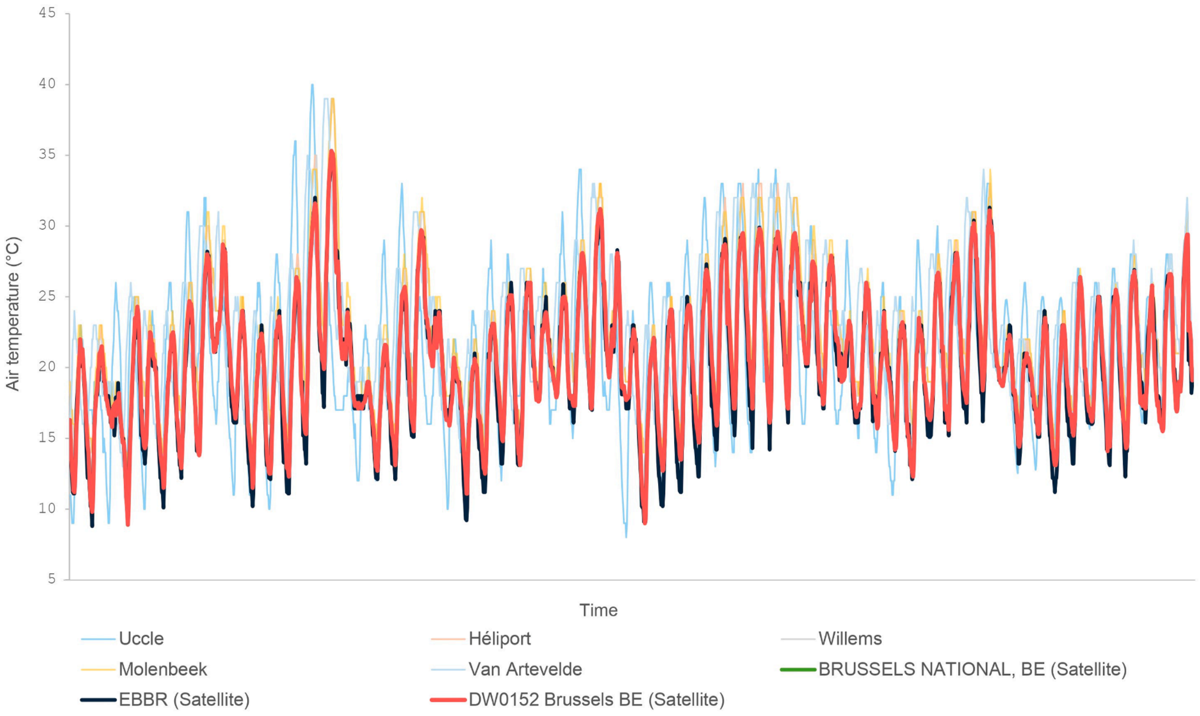
Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.scs.2025.106974.

Appendix A

Figure A.

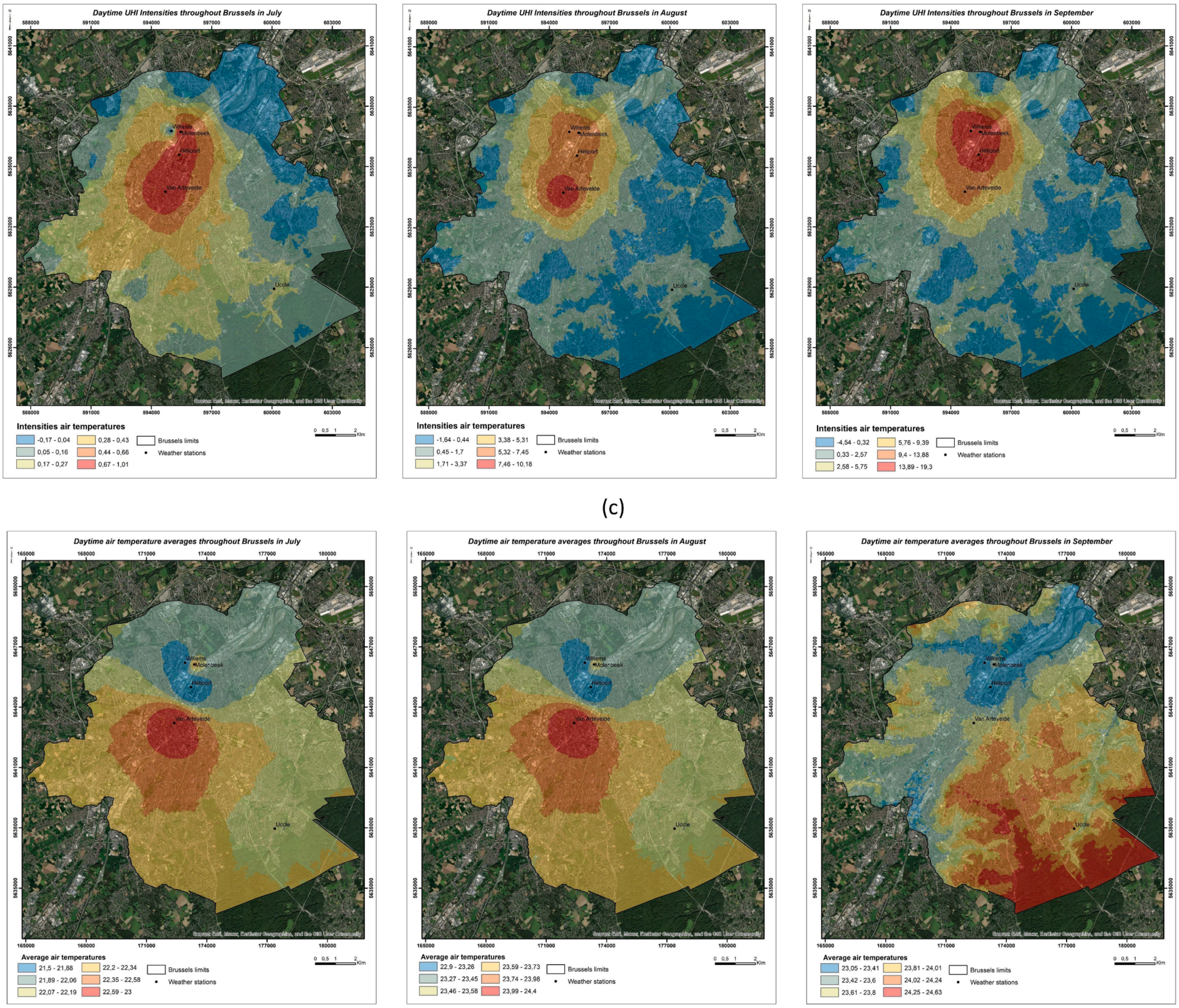


WS (SATELLITE DATA)	DISTANCE	LATITUDE	LONGITUDE
BRUSSELS NATIONAL, BE	11.3 KM	50.901	4.484
EBBR	14.5 KM	50.90	4.53
DW0152 Brussels, BE	16.1 KM	50.902	4.534

Fig. A. Temperature hourly variations between field measurements taken from the implemented weather stations and satellite datasets acquired from three non-urban weather stations: Brussels National Airport, EBBR, and DW0152 during the study period.

Appendix B

Fig. B illustrates the daytime monthly UHI intensities versus the air temperature (T_{air}) daytime monthly averages from July to September 2022.



(c)

(d)

Fig. B. Mapping of monthly daytime UHI intensities and air temperature averages throughout Brussels from July to September 2022.

Data availability

Dataset on urban microclimate in Brussels Belgium (Original data) (Dataverse)

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