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RESEARCH

Dynamics of urban heat island intensity in Lecce, Italy: seasonal, diurnal and heat wave influence

Gianluca Pappaccogli[1] · Francesco Giangrande[1] · Antonio Esposito[1] · Antonio Donateo[2] · Piero Lionello[1] · Riccardo Buccolieri[1,2]

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Abstract
This study investigates the impact of Heat Waves (HWs) on Urban Heat Island Intensity (UHII) in Lecce, a Mediterranean city in southern Italy. UHII was assessed using air temperature data from six weather stations over a four-year period (2020–2023). The results indicate that UHII is generally higher in winter and spring, with the ARPA (Environmental Protection Regional Agency) station consistently showing the highest values, particularly in summer, attributed to urban characteristics. The diurnal cycle of UHII reveals a peak in the early morning at most stations, followed by a decrease to near zero or slightly negative values during midday. Evening values then increase and persist throughout the night. Stations surrounded by green areas or located in suburban settings recorded the lowest UHII values. A total of eleven HWs occurred during the study period, with an average duration of 10 days. UHII was significantly more intense during HWs at all stations, with the greatest average observed at the ARPA station (2.60 °C) and the smallest at the LST (Liceo Scientifico Tabacchi) station (0.74 °C). These findings highlight the significant impact of HWs on UHI intensification in Lecce, especially in densely developed areas compared to suburban regions. This study emphasizes the importance of investigating UHII dynamics in Mediterranean cities to develop strategies for mitigating the Urban Heat Island (UHI) effect during extreme heat events.

Keywords Extreme heat events · Urban Heat Island Intensity (UHII) · Urban overheating · Lecce

✉ Gianluca Pappaccogli
gianluca.pappaccogli@unisalento.it

1 Dipartimento di Scienze e Tecnologie Biologiche ed Ambientali, University of Salento, Lecce, Italy

2 Institute of Atmospheric Sciences and Climate (ISAC), National Research Council (CNR), Lecce, Italy

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1 Introduction

Urban Heat Island (UHI) is a phenomenon in which cities and towns experience higher air temperatures compared to nearby rural locations (Jiang et al. 2019). It has been highlighted that the primary factors controlling UHI are land cover change, urban sprawl and anthropogenic heat (Stewart and Oke 2012) released by air conditioning systems, industrial activities and motor vehicles. Other determining factor is the scarcity or lack of green areas and vegetation. UHI Intensity (UHII) has commonly been defined as the air temperature difference between urban and rural places (Martin-Vide et al. 2015). In a context of climate change, cities face major challenges, such as mitigating overheating, optimising energy consumption and improving the thermal comfort of inhabitants. Indeed, the Urban Heat Island Intensity (UHII) is exacerbated during extreme events, such as Heat Waves (HWs) events (Cheval et al. 2024), defined as a period of six consecutive days with maximum air temperatures exceeding the 90th percentile of the reference period (1991–2020) (Fischer and Schär 2010). HWs exacerbate the air temperatures and trigger major impacts on the socio-ecological and sanitary systems, requiring specific adaptation mechanisms of the economy and society, particularly in areas highly vulnerable to extreme weather events associated with climate change (Cheval et al. 2024). Jiang et al. (2019) found that HWs intensified nighttime UHII by 0.9 °C in Beijing and 0.8 °C in Guangzhou, and daytime UHII by 0.9 °C in Shanghai, from June to August 2013–2015. This study was conducted on Lecce, a city in the Mediterranean region that, in a context of rising global air temperatures and intensifying HWs, emerges as a hotspot that is experiencing an increase in the frequency and intensity of these extreme heat events (Delgado-Capel et al. 2024). A previous study by Donateo et al. (2023), investigated the UHI in Lecce, showing a pronounced deterioration in thermal comfort over the last decade. The objective of this work is to assess the UHI of the city of Lecce over the period 2020–2023, focusing on the impact of HWs on UHII, quantifying the latter's increases and monthly distribution.

2 Methods

2.1 Study area

The area of interest is Lecce, a city with approximately 94,000 inhabitants (ISTAT 2022, accessed on 20th June 2024) and located in south-eastern Italy (40° 21′ 11" N, 18° 10′ 21" E) (Fig. 1). Lecce is situated on a flat area, ranging from 40 to 50 m above sea level; it is 13 km from the coast of the Adriatic Sea and 25 km from the coast of the Ionian Sea (Donateo et al. 2023). The city presents a radial development with a compact and irregular historic centre composed of narrow streets, whereas neighbourhoods built in the last decades are compact but regular. The historical centre of the city is characterised by buildings of calcareous tufa and streets paved with local stone; both materials have a high thermal capacity and heat conductivity (Esposito et al. 2023). Lecce presents hot and dry summer and mild and wet winter (Csa class) (World Map of the Köppen-Geiger climate classification 2024, accessed on 20th June 2024), belonging to a typical Mediterranean climate. Also, extreme events such as Heat Waves (HWs) occur in the Salento peninsula during the summer due to the domination of a subtropical high-pressure system for several days (Giorgi and Lionello 2008).

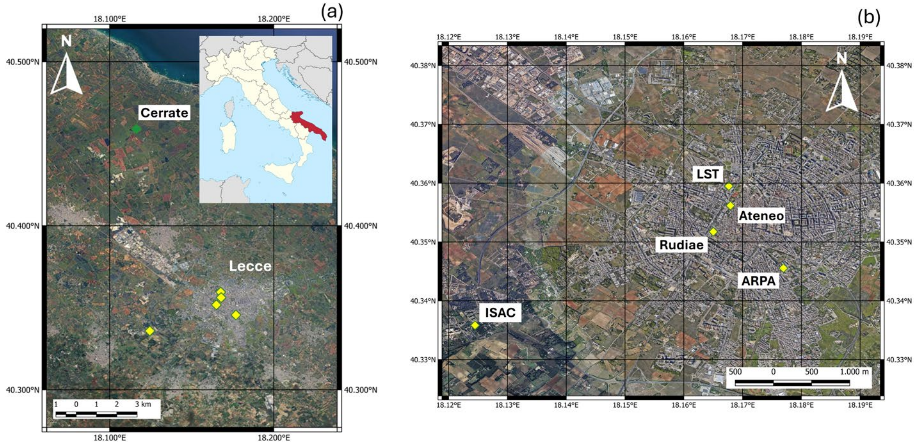

Fig. 1 **a** Location of Lecce in southeast Italy (background map: Google Earth); (**b**) close-up view of Lecce's urban area. Green diamond indicates rural weather station, while yellow diamonds mark urban weather stations

2.2 Measurement sites

UHII was estimated using air temperature values from six automated weather stations operated by different public and research agencies, over a four-year period (January 2020 to December 2023). The logging intervals varied from 10 to 30 min, whereas the percentage of verified data ranged from 40% (Rudiae) to 98% (ISAC). The final dataset consists of 30-min values at all stations, averaging the data from shorter logging time. The raw half-hour data underwent despiking to remove outliers and linear interpolation to fill gaps under two hours. Four of the weather stations are in the urban area and named ARPA (40°20′44.23"N, 18°10′37.54"E), Ateneo (40°21′22.30"N, 18°10′4.72"E), Rudiae (40°21′6.25"N, 18° 9′54.08"E), and Liceo Scientifico Tabacchi (LST) (40°21′34.19"N, 18°10′3.58"E), one is in a suburban area, ISAC (40°20′8.90"N, 18° 7′28.15"E), and yet another in a rural environment, Cerrate (40°27′32.26"N, 18° 6′58.77"E). Donateo et al. (2023) provide a detailed description of each urban and suburban station, except for the Cerrate station. This station is situated near the "Abbazia di Santa Maria di Cerrate" (40°27′31.16"N, 18° 6′56.30"E), approximately 12 km from the center of Lecce, in a rural setting surrounded by forests and agricultural fields. UHII was assessed from air temperature differences between urban/suburban and rural sites, using the processed air temperature values, as defined below:

$$UHII = T_u - T_r$$

where T_u is the air temperature of the selected urban/suburban station and T_r is the air temperature of the rural reference station (Cerrate). UHII is expressed with a temporal resolution of 30 min. The seasonal and daily cycle of UHII was subsequently examined. In this study, HW periods were defined according to Fischer and Schär, 2010. HW and Non Heat Waves NHW periods were compared by using the Student's t-test after checking for normality distribution of data (Shapiro–Wilk's test). Values of p lower than 0.05 were considered significant.

3 Results and discussion

3.1 UHII seasonal characterization

Table 1 presents the UHII values for the five selected urban/suburban stations, averaged for each season and each year. We studied the average UHII for each season across four years (2020–2023). Winter (December, January, February, DJF) and autumn (September, October, November, SON) have the highest average UHII, at 0.99 °C and 0.92 °C respectively. Spring (March, April, May, MAM) show slightly lower averages (0.89 °C), while summer (June, July, August, JJA) has the lowest (0.71 °C).

Out of all the stations, ARPA presents the highest values, especially in summer (averaging 1.97 °C), while the LST station has the lowest average UHII (0.37 °C), likely due to its surrounding vegetation. The data indicates that the UHII is generally higher in winter (ranging from 0.92 °C to 1.04 °C) and lowest in summer (ranging from 0.47 to 1.00 °C). The ARPA station consistently records the highest values, especially during summer. Over the four-year period, there is a slight decrease in the annual average UHII, mainly because of missing data from the ARPA station. Seasons with less than 70% valuable data were excluded from Table 1 and UHII analysis.

3.2 UHII diurnal characterization

The diurnal cycle of the UHII from 2020 to 2023 (Fig. 2) shows that the maximum UHII occurs in the early morning (6:00–7:00 LT) at most stations, except for ARPA, which peaks at night (23:00–24:00 LT). After the morning peak, UHII values drop to near zero or slightly negative during midday (13:00–16:00 LT), except for ARPA, which maintains UHII slightly above 1.00 °C. Notably, at 15:00 L.T., all stations except ARPA show slightly negative values, with Rudiae recording values as low as -0.50 °C. This phenomenon identifies the occurrence of an urban cold island, especially in areas of the historic centre characterised by the presence of limestone material with high thermal capacity and light colours. Evening values increase and persist throughout the night due to heat release from urban surfaces. The LST and ISAC stations present the lowest average UHII values, being surrounded by green areas and suburban settings, respectively. In contrast, ARPA shows the highest values due to its location near a sunlit wall and an asphalt parking lot, contributing to significant overheating. These findings align with Donateo et al. (2023), despite using a different rural reference station.

3.3 Impact of heat waves on UHII

As the goal of the present work is to assess the impact of HWs on UHII, heat waves have been defined according to Fischer and Schär (2010). The 90th percentile was calculated using meteorological data from LST stations for the period 1991–2020 throughout the year. The station is suitable for long-term measurements as the time series is homogeneous according to the homogeneity tests (Petit 1979, Buishand 1982 and Khaliq and Ouarda 2007). The subsequent analysis on HWs focuses on the summer season (JJA), when these phenomena pose a health risk to urban dwellers. Specifically, during the summer seasons (JJA) from 2020–2023, a total of eleven HWs occurred, with an average duration of approximately 10 days and an average daily maximum air temperature of 34.80 °C. Two HWs occurred in 2020 while three in 2021, 2022 and 2023. The year with the most HWs days (36 days) was 2022, while 2021 shows the highest average daily maximum air temperatures during HWs periods (36.00 °C).

Table 1 UHII (°C) estimated as the difference between Cerrate and the five urban/suburban station. Percentage of verified air temperature data: ARPA = 47%, Ateneo = 99%, Rudiae = 40%, LST = 68%, ISAC = 98%, Cerrate = 98%

	2020				2021				2022				2023			
Stations	DJF	MAM	JJA	SON	DJF	MAM	JJA	SON	DJF	MAM	JJA	SON	DJF	MAM	JJA	SON
ARPA	1.68	1.71	1.90	1.69	1.61	1.45	2.03	1.63	-	-	-	-	-	-	-	-
Ateneo	1.28	1.05	0.70	1.21	1.22	1.04	0.94	1.07	1.44	1.29	0.74	1.01	1.49	1.15	0.71	1.16
Rudiae	-	-	-	-		-	-	-	1.17	1.07	0.45	0.77	1.19	0.81	0.44	0.95
LST	0.44	0.47	0.23	0.50	0.65	0.54	0.50	-	0.56	0.64	-	-	-	-	0.39	0.76
ISAC	0.26	0.58	0.39	0.49	0.68	0.50	0.53	0.50	0.62	0.55	0.55	0.48	0.45	0.54	0.32	0.68
Seasonal	0.92	0.95	0.80	0.97	1.04	0.88	1.0	1.07	0.95	0.89	0.58	0.75	1.04	0.83	0.47	0.89
Annual	0.91				1.00				0.79				0.81			

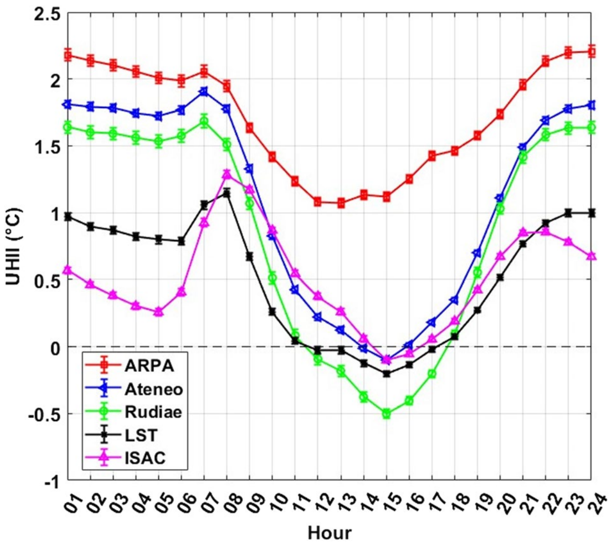

Fig. 2 Hourly diurnal pattern for UHII (°C) from January 2020 to December 2023. The maximum standard error is 0.06 °C

Figure 3 shows UHII boxplots for different years during HWs and NHWs periods for the urban/suburban stations. Overall, UHII is highest during HWs at all stations and for all years analysed. Station averages during HWs range from 0.74 °C (LST) to 2.60 °C (ARPA), while NHWs averages vary from 0.23 °C (LST) to 1.79 °C (ARPA). ISAC shows the smallest difference (0.48 °C) in UHII between HWs and NHW periods. For other stations, this difference ranges from 0.51 °C to 0.81 °C. Looking at the distribution of the 75th percentiles, ARPA shows the highest value (above 4.00 °C) during HWs periods in 2020, while LST presents the lowest average (1.21 °C), with a minimum of 0.76 °C during NHWs. Ateneo and ISAC show average 75th percentiles for periods with HWs ranging from 2.35 °C to 1.49 °C respectively, while during NHWs periods ranging from 1.55 °C (Ateneo) to 1.07 °C (ISAC). Statistical tests revealed significant differences (p-value range: $5 \cdot 10^{-4}$ to 0.02) in UHII between HWs and NHWs periods for all stations except ARPA.

4 Conclusions

This study assesses the impact of Heat Waves (HWs) on the intensification of the UHI in the Mediterranean city of Lecce, Italy. The UHII was analysed by examining seasonal, annual, and daily dynamics. The highest average seasonal UHII values were recorded during the winter months (DJF) with an average of 0.99 °C, while the lowest average values were recorded during the summer months (JJA) with an average of 0.71 °C. This difference was likely due to anthropogenic heat and lower atmospheric mixing, which is mainly related to less ventilation and turbulence development, as reported by Donateo et al. (2019). It is worth emphasizing that the absence of data for some seasons affects both seasonal and annual UHII analyses. The diurnal cycle showed a pattern consistent with the natural cycle of UHI. A comparison using the Student t-test between UHII with and without HWs showed significant differences at all selected urban/suburban weather stations except ARPA. The results indicate that UHI during HWs was more pronounced in densely built-up areas as ARPA (0.73 °C) than in suburban areas, such as ISAC (0.49 °C). The results of

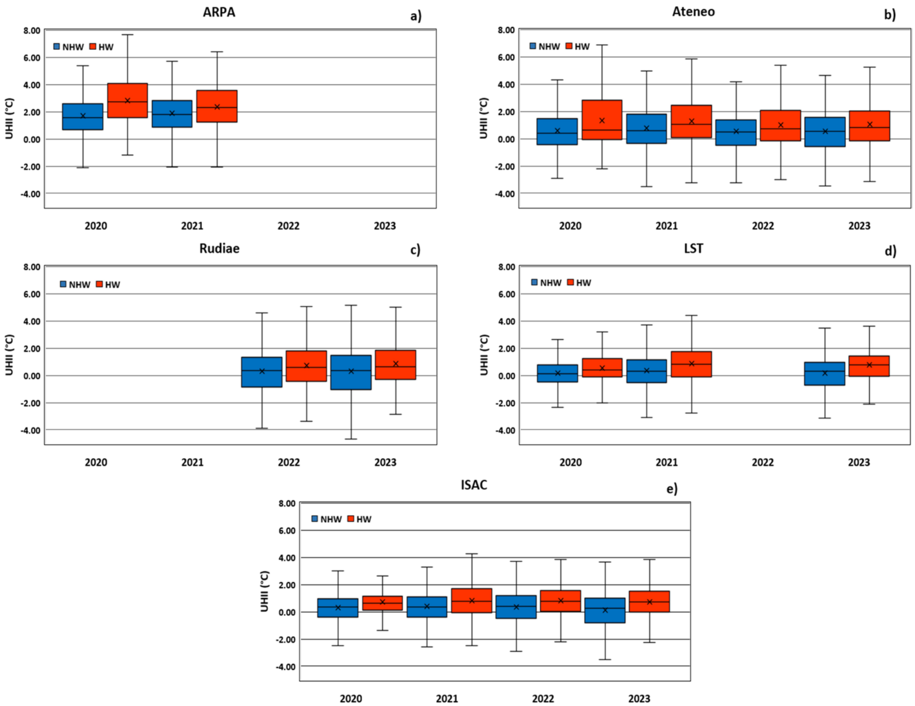

Fig. 3 Box plots of hourly air temperature differences between Cerrate and (**a**) ARPA, (**b**) Ateneo, (**c**) Rudiae, (**d**) LST and (**e**) ISAC. The results refer to the periods of HW and, NHW. The bottom and the top of the boxes represent, respectively, the first and the third quartiles (Q1 and Q3), the continuous line the median, and "x" the mean. The ends of the whiskers represent, the maximum and minimum values within 1.5 times the IQR above Q3 and below Q1, respectively

this study align with those of a similar study on Rome (Di Bernardino et al. 2023), where the nighttime (UHII) during the summer of 2022 was significantly higher on HW days than on NHW days, while average daily UHII showed no significant difference. Founda and Santamouris (2017) found that HWs amplified the UHII up to 3.5 °C compared to normal summer conditions in Athens during the summer of 2012. City size and climate may explain the contrasting results with respect to the present study. Such studies are crucial for urban areas like Lecce, and more broadly for cities with a Mediterranean climate, in assessing the exacerbation of the UHI effect due to summer HWs This research can serve as a foundation for more detailed studies on UHI during HWs, suggesting the need to explore such dynamics in different cities across the Mediterranean region.

The complexity of the UHI process requires an integrated approach that includes modelling and remote sensing to gain insights into processes that cannot be identified with conventional measurements. Future analyses should investigate the processes enhancing UHI, focusing on extreme values. It is crucial to consider ventilation, a key factor affecting the distribution and intensity of UHI. Characterizing the duration and intensity of these phenomena is important for assessing thermal comfort and peak energy consumption in urban areas.

Author contributions G.P., F.G., R.B. wrote the main text of the manuscript and prepared figures and tables. A.E., A.D., P.L., contributed to review the manuscript.

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Data availability Data will be made available on request.

Declarations

Competing interests The authors declare no competing interests.

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