Bull. of Atmos. Sci.& Technol. (2024) 5:10
https://doi.org/10.1007/s42865-024-00071-0

RESEARCH

# Assessment of the urban pollution island intensity in Rome (Italy) from in-situ PM measurements

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Received: 8 May 2024 / Accepted: 5 July 2024

## Abstract

The Urban Pollution Island (UPI), describing the temporal and spatial distribution of pollutants' concentration attributed to the presence of urban features and activities, is one of the major problems affecting urban areas and has become more severe with rapid urbanization. To correctly evaluate the UPI Intensity (UPII), i.e., the difference in pollution concentration between the urban agglomeration and its rural surroundings, it is crucial to carefully select rural and, above all, urban reference stations, as local factors such as orography, location of the air quality monitoring stations, and street orientation can significantly impact UPII values. In this work, the UPII in Rome (Italy) is determined using daily-averaged concentrations of $PM_{10}$ and $PM_{2.5}$ collected by in-situ stations over the period 2018–2023. Three different methods for the assessment of UPII are tested and compared by varying the sub-set of selected urban stations, according to their environmental classification. The approach proposed will have significant implications on the management of urban environment and on the tailored design of urban air quality improvement strategies. Results show slight differences in the monthly-averaged concentrations of both $PM_{10}$ and $PM_{2.5}$ between the "urban traffic" and "urban background" stations, suggesting that the proximity of the emission sources to the monitoring stations moderately influences the concentrations, potentially due to limited ventilation within street canyons, which can inhibit mixing processes. The annual variation of UPII reveals that $PM_{10}$ is more sensitive to the selection of the stations particularly during winter, when the differences between the three assessment methods reach 100%. Our findings also indicate that, in the case of Rome, using the largest number of stations available in the urban area could enhance the UPII evaluation, taking into consideration the urban structure and the specific characteristics of local emission sources. The results presented here, although related to a single city, demonstrate that the selection of urban stations for the evaluation of UPII is not straightforward and requires further investigation.

**Keywords** Air quality · Atmospheric pollution · Particulate matter · Urban Pollution Island Intensity · Near-surface concentration

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# 1 Introduction

Currently, urban areas host more than 50% of the world's population (Jansson 2013), with projections indicating a doubling of this percentage in the next decades (UN 2018). Undoubtedly, the assessment of the impacts of accelerated urbanization and land cover changes on human health and the environment are among the major challenges that the scientific community has to face to design tailored strategies for improving air quality and addressing the increase in temperature caused by the ongoing climate change.

Urban Heat Island (UHI) and Urban Pollution Island (UPI) are both phenomena mostly affecting urbanized areas, because of the development of human settlements, land use, transport, and high population density.

UHI manifests as a higher atmospheric warming in densely populated areas compared to rural surroundings, primarily due to the large extent of built-up surfaces, like concrete and asphalt, with greater heat capacity and lower evapotranspiration rates compared to natural surfaces (Oke 1973). Furthermore, the conformation of buildings can modify near-surface atmospheric circulation, limiting ventilation and exacerbating the accumulation of pollutants near the ground (Di Bernardino et al. 2021). To characterize the UHI, the Urban Heat Island Intensity (UHII), defined as the temperature difference between a representative urban area and the rural background, was introduced. The scientific debate regarding the best approach for assessing the UHII is still open (Tzavali et al. 2015; Li et al. 2018a; Cecilia et al. 2023).

The UPI concept was recently introduced by Crutzen (2004) to describe the temporal and spatial distribution of pollutants' concentration attributed to the presence of urban features and activities, responsible for the emission of harmful substances, such as particulate matters (PM). Specifically, PM consist of solid and liquid particles with an aerodynamic diameter between 0.1 μm and ~100 μm, which tend to remain suspended in the air. The term $PM_{10}$ identifies particles with an aerodynamic diameter < 10 μm, while the term $PM_{2.5}$ refers to particles with an aerodynamic diameter < 2.5 μm. By analogy with the UHII, the Urban Pollution Island Intensity (UPII) is defined as the difference between the concentration of the pollutant under investigation in the urban area and in its rural surroundings. The procedure on how UPII should be determined is still under discussion (Li et al. 2020a; Mendez-Astudillo et al. 2022), with one of the most debated aspects being the appropriate selection of urban and rural stations used for its evaluation (Li et al. 2020b). In fact, the UPII can be significantly influenced by several factors including local orography, position of the air quality monitoring stations, street canyons orientation, streets width, meteorological conditions, and proximity of the emission sources. Li et al. 2018b, 2020b) calculated the UPII for $PM_{10}$ in Berlin (Germany) through a combined analysis of in-situ and remote sensing observations of aerosol and meteorological variables, also relating the UPII to the urban-rural differences in the downward longwave radiation. Li et al. (2020a) evaluated the UPII in Beijing (China) from PM measurements and investigated the correlation between UPII and UHII, emphasizing that UPII is more sensitive to the selection of rural background stations compared to the UHII. Singh et al. (2022) examined the spatial variability in $PM_{10}$ and $PM_{2.5}$ concentration over Delhi (India) and determined the daily and seasonal evolution of UPII considering separately the urban traffic and urban background stations.

The main objective of this work is to assess the air quality in the metropolitan area of Rome (Italy) using in-situ measurements of $PM_{10}$ and $PM_{2.5}$ collected over the period

2018–2023. Several approaches are tested to estimate the daily-averaged UPII by modifying the subset of urban stations, depending on their environmental classification. To the best of the authors' knowledge, this is the first study focused on the spatial-temporal assessment of the UPII from PM observations in Rome and can, therefore, be considered a benchmark for investigating processes driving the UPI and its association with the UHI.

The paper is structured as follows: Sect. 2 describes the area under investigation, the air quality dataset, and the procedure for the UPII evaluation. In Sect. 3, the main results are presented and discussed. In Sect. 4, conclusions and possible outlooks are summarized.

## 2 Materials and methods

Rome (Lat. 41.90 °N, Lon. 12.50 °E) is located in central Italy and hosts approximately 2.8 million inhabitants in its metropolitan area. Previous studies demonstrated that the urban centre experiences the UHI phenomenon (Di Bernardino et al. 2022; Cecilia et al. 2023) and high levels of air pollution attributable to local anthropogenic emissions (Di Bernardino et al. 2021), often compounded by the long-range transport of Saharan dust (Barnaba et al. 2017).

Here, the daily-averaged concentrations of $PM_{10}$ and $PM_{2.5}$, provided by in-situ stations belonging to the air quality monitoring network managed by the Regional Environmental Protection Agency of Lazio region (ARPA Lazio, http://www.arpalazio.gov.it/ambiente/aria/, last accessed on 07 March 2024), are examined. Details about the air quality stations are summarized in Table 1, while their location is shown in Fig. 1.

The environmental classification presented in Table 1, provided by ARPA Lazio, is here used to define the different sub-sets of urban stations. Specifically, stations are labelled as: (i) "urban traffic", if they are mainly influenced by traffic emissions from neighbouring roads with medium-high traffic intensity; (ii) "urban background", if they are mainly influenced by the integrated contribution of all the sources located upwind of the station with respect to the predominant wind directions at the site; and (iii) "rural background", if they can be assumed as representative of the rural environment, being at a distance greater than 50 km from the main emission sources. An example of the environment surrounding the three types of stations is shown in the right panels of Fig. 1. Daily averaged data, quality checked by ARPA Lazio (with an uncertainty on the mass measurement of 10 µg) underwent

**Table 1** Information on the air quality stations managed by ARPA Lazio considered in the present study

| ID | Name | Lat (°*N*) | Lon (°E) | Elevation (m a.s.l.) | Environment classification | Variable |
|---|---|---|---|---|---|---|
| ARPA-02 | Preneste | 41.89 | 12.54 | 37 | urban background | $PM_{10}$ |
| ARPA-03 | Corso Francia | 41.95 | 12.47 | 43 | urban traffic | $PM_{10}$, $PM_{2.5}$ |
| ARPA-05 | Magna Grecia | 41.88 | 12.51 | 49 | urban traffic | $PM_{10}$ |
| ARPA-08 | Cinecitta | 41.86 | 12.57 | 53 | urban background | $PM_{10}$, $PM_{2.5}$ |
| ARPA-39 | Villa Ada | 41.93 | 12.51 | 50 | urban background | $PM_{10}$, $PM_{2.5}$ |
| ARPA-40 | Castel Di Guido | 41.89 | 12.27 | 61 | rural background | $PM_{10}$, $PM_{2.5}$ |
| ARPA-47 | Fermi | 41.87 | 12.47 | 26 | urban traffic | $PM_{10}$ |
| ARPA-48 | Bufalotta | 41.95 | 12.53 | 41 | urban background | $PM_{10}$ |
| ARPA-49 | Cipro | 41.91 | 12.45 | 31 | urban background | $PM_{10}$, $PM_{2.5}$ |
| ARPA-55 | Tiburtina | 41.91 | 12.55 | 32 | urban traffic | $PM_{10}$ |
| ARPA-56 | Arenula | 41.89 | 12.47 | 31 | urban background | $PM_{10}$, $PM_{2.5}$ |

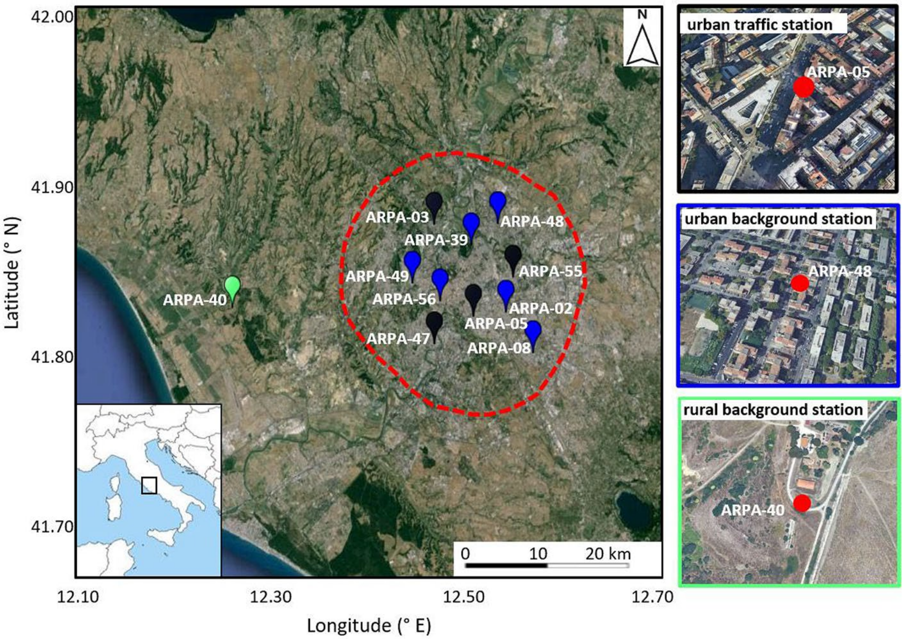


**Fig. 1** Left: map of the metropolitan area of Rome (red dotted line) and location of air quality stations considered in this study, labelled following the ID codification in Table 1. Black, blue, and green markers depict urban traffic, urban background, and rural background stations, respectively. Right: aerial view of the surroundings of an urban traffic station (ARPA-05, upper panel), an urban background station (APRA-48, central panel), and the rural background station (ARPA-40, lower panel)

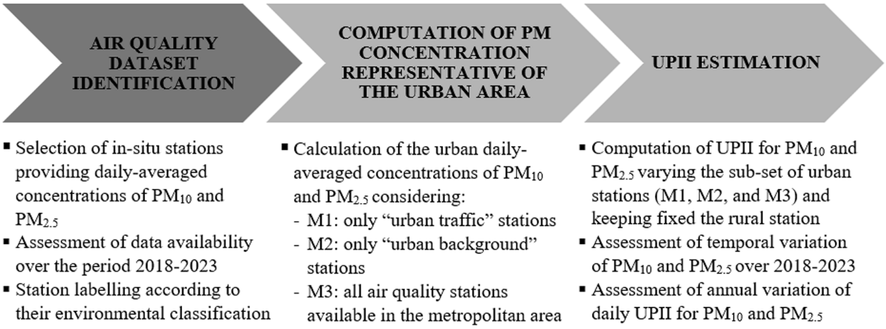
**Table 2** List of the stations considered for the evaluation of UPII with different methods, labelled according to the ID codification in table 1

| Method | Urban stations | Rural station |
|---|---|---|
| Method 1 (M1) | urban traffic: ARPA-03, ARPA-05, ARPA-47, ARPA-55 | rural background: ARPA-40 |
| Method 2 (M2) | urban background: ARPA-02, ARPA-08, ARPA-39, ARPA-48, ARPA-49, ARPA-56 | rural background: ARPA-40 |
| Method 3 (M3) | urban traffic + urban background: ARPA-02, ARPA-03, ARPA-05, ARPA-08, ARPA-39, ARPA-47, ARPA-48, ARPA-49, ARPA-55, ARPA-56 | rural background: ARPA-40 |

additional visual inspection in this study. For all the sites considered, missing data is less than 5% for both $PM_{10}$ and $PM_{2.5}$ and is randomly distributed throughout the investigation period.

To estimate the UPII, three approaches are proposed and compared. The rural station (ARPA-40, Castel di Guido) is kept fixed, while different subsets of urban stations are selected, based on the environmental classification provided by ARPA Lazio, as summarized in Table 2.

In summary, Method 1 (M1) considers only the “urban traffic” stations as characteristic of the urban area, Method 2 (M2) includes only the “urban background” stations, and Method 3 (M3) evaluates the UPII using all the air quality stations available in the metropolitan area. In each



- Selection of in-situ stations providing daily-averaged concentrations of $PM_{10}$ and $PM_{2.5}$
- Assessment of data availability over the period 2018-2023
- Station labelling according to their environmental classification

- Calculation of the urban daily-averaged concentrations of $PM_{10}$ and $PM_{2.5}$ considering:
  - M1: only "urban traffic" stations
  - M2: only "urban background" stations
  - M3: all air quality stations available in the metropolitan area

- Computation of UPII for $PM_{10}$ and $PM_{2.5}$ varying the sub-set of urban stations (M1, M2, and M3) and keeping fixed the rural station
- Assessment of temporal variation of $PM_{10}$ and $PM_{2.5}$ over 2018-2023
- Assessment of annual variation of daily UPII for $PM_{10}$ and $PM_{2.5}$

**Fig. 2** Flowchart of the proposed methodology

**Table 3** Main statistics of the daily-averaged $PM_{10}$ and $PM_{2.5}$ concentrations over the period 2018–2023

| | $PM_{10}$ | | | $PM_{2.5}$ | | |
|---|---|---|---|---|---|---|
| Station ID | Mean | Standard deviation | Max | Mean | Standard deviation | Max |
| ARPA-02 | 26.69 | 12.92 | 149.00 | n.a. | n.a. | n.a. |
| ARPA-03 | 24.33 | 10.10 | 80.00 | 13.49 | 7.15 | 50.00 |
| ARPA-05 | 24.16 | 11.50 | 89.00 | n.a. | n.a. | n.a. |
| ARPA-08 | 26.28 | 12.67 | 129.00 | 14.90 | 9.26 | 92.00 |
| ARPA-39 | 22.78 | 9.99 | 77.00 | 12.5 | 7.2 | 61 |
| ARPA-40 | 20.05 | 8.89 | 88.00 | 11.00 | 5.93 | 45.00 |
| ARPA-47 | 28.50 | 12.09 | 93.00 | n.a. | n.a. | n.a. |
| ARPA-48 | 25.66 | 12.71 | 111.00 | n.a. | n.a. | n.a. |
| ARPA-49 | 23.68 | 11.44 | 98.00 | 12.65 | 7.47 | 62.00 |
| ARPA-55 | 30.08 | 14.56 | 112.00 | n.a. | n.a. | n.a. |
| ARPA-56 | 23.77 | 10.73 | 95.00 | 13.04 | 7.61 | 60.00 |
| urban traffic | 26.77 | 12.06 | 112.00 | 13.49 | 7.15 | 50.00 |
| urban background | 24.81 | 11.74 | 149.00 | 13.27 | 7.89 | 92.00 |
| urban traffic + urban background | 25.59 | 11.87 | 149.00 | 13.32 | 7.74 | 92.00 |

case, the PM concentration representative of the urban area is obtained by averaging the observations of the different stations considered. It is worth highlighting that, since $PM_{2.5}$ measurements are not carried out at all stations, the urban subset for $PM_{10}$ and $PM_{2.5}$ may differ within the same method. These different methods allow for the comparison of daily and seasonal time-series of UPII, providing useful information to select the most significant stations for the area under investigation. The flowchart adopted in this study is shown in Fig. 2.

## 3 Results and discussion

Table 3 summarizes the main statistics of the daily-averaged $PM_{10}$ and $PM_{2.5}$ concentrations collected by the selected ARPA Lazio stations between 2018 and 2023. Figure 3 shows the monthly-averaged concentrations of $PM_{10}$ and $PM_{2.5}$ for stations grouped according to their environmental classification.

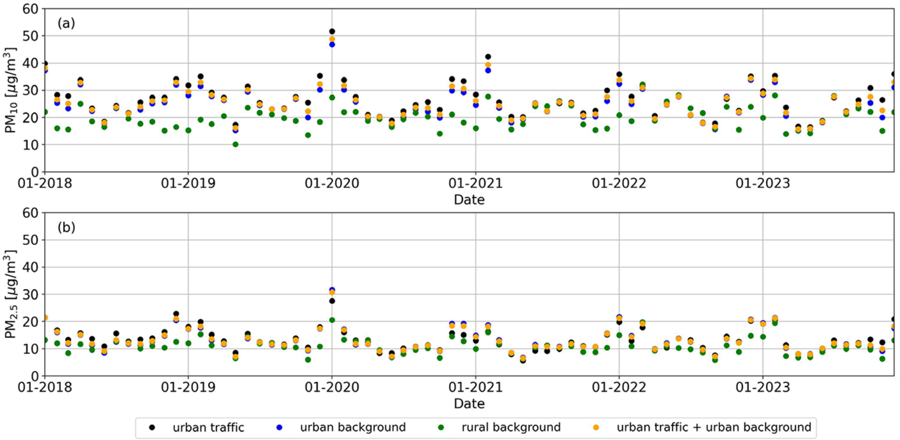


**Fig. 3** Monthly-averaged concentrations of (**a**) $PM_{10}$ and (**b**) $PM_{2.5}$ observed at "urban traffic" stations (black markers), "urban background" stations (blue markers), "rural background" stations (green markers), and "urban traffic" and "urban background" stations (orange markers) from 2018 to 2023

As expected, the highest PM concentrations are recorded in the urban centre, with mean concentrations slightly higher in the "urban traffic" stations (26.77 $\mu g/m^3$ and 13.04 $\mu g/m^3$ for $PM_{10}$ and $PM_{2.5}$, respectively) compared to the "urban background" ones (24.81 $\mu g/m^3$ and 13.27 $\mu g/m^3$ for $PM_{10}$ and $PM_{2.5}$, respectively). When averaging all the stations in the metropolitan area, the values of $PM_{10}$ and $PM_{2.5}$ are intermediate. Nonetheless, the slight differences between the "urban traffic" and "urban background" stations, as evident from the monthly-averaged time series shown in Fig. 3, suggest that the proximity of the emission sources to the monitoring stations might moderately influence the concentrations. This aspect could be attributed to the interaction between street canyons orientation and local ventilation, which might limit pollutants' mixing processes and will be further explored.

It is worth noticing that this dataset also includes PM measurements collected during local events (e.g., fires) that can influence a single station, altering the statistics. Furthermore, the statistics calculated in this preliminary analysis are intended to provide an overall and generalized picture of air quality conditions in Rome. Hence, they do not account for the influence of atmospheric weather patterns (e.g., sea/land breeze regime, persistence of high-pressure conditions, calm winds) or seasonal events (e.g., dust outbreaks, transport of ash from wildfires), which can impact the PM average and maximum concentrations.

The annual cycle of UPII (Fig. 4a and b) shows similar trends for $PM_{10}$ and $PM_{2.5}$, although with more marked seasonal variation observed for $PM_{10}$. For both variables, UPII reaches maximum values in winter and minimum values in summer. The highest wintertime UPII values (40 $\mu g/m^3$ and 10 $\mu g/m^3$ for $PM_{10}$ and $PM_{2.5}$, respectively) are attributable to more intense local emissions (e.g., domestic heating), to the limited development of the urban mixed layer compared to summer, and to recurrent events of persistent atmospheric stability, which can determine strong accumulation of pollutants near the ground. On the contrary, during summer, the intense daytime convection, the greater ventilation - typically associated with the sea breeze regime - and the reduction of local emissions contribute to the dispersion of aerosols, resulting in more evident spatial homogeneity. In this last case,

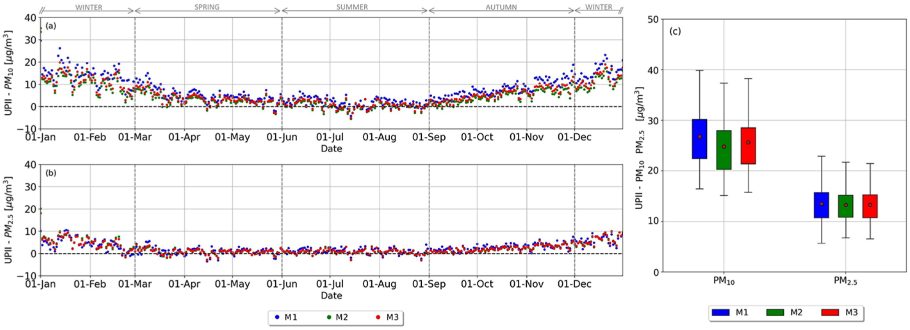


**Fig. 4** Annual variation of daily UPII for (**a**) $PM_{10}$ and (**b**) $PM_{2.5}$ evaluated with methods detailed in Sect. 2 and (**c**) boxplots of UPII. The red dots depict the mean values, the lower and upper boundaries of the boxes denote the 25th (Q1) and 75th (Q3) percentiles, and the lower and upper whiskers are set to minimum and maximum of the data set provided that they are not outliers - outside the interval between (Q1–1.5IQR) and (Q3 + 1.5IQR), where IQR is the interquartile range; in that case the whisker are set to the latter ones

UPII can even assume negative values, indicating higher aerosol concentrations in the rural environment compared to downtown Rome. The latter aspect might also be influenced by the agricultural activities typical of the summer season carried out near the rural reference station and requires further investigation. For $PM_{10}$, the differences between M1 and M2 reach 100% in the winter months but drop to 20% during summer. Meanwhile, for $PM_{2.5}$, the variations consistently remain below 20%, suggesting greater spatial homogeneity.

As demonstrated by boxplots in Fig. 4c, the mean value of UPII reaches its maximum when only "urban traffic" stations are considered (26.8 $\mu g/m^3$ and 13.5 $\mu g/m^3$ for $PM_{10}$ and $PM_{2.5}$, respectively), and its minimum when only "urban background" sites are used (24.8 $\mu g/m^3$ and 13.1 $\mu g/m^3$ for $PM_{10}$ and $PM_{2.5}$, respectively). Intermediate values are observed when all urban stations are averaged (25.6 $\mu g/m^3$ and 13.3 $\mu g/m^3$ for $PM_{10}$ and $PM_{2.5}$, respectively). Furthermore, the selection of urban stations mainly affects UPII for $PM_{10}$, while for $PM_{2.5}$ mean values and reference percentiles do not differ significantly.

Based on these findings, it can be concluded that the method M3, involving a greater number of stations distributed through the city centre, is more representative of the typical regional situation without losing peculiar information on the characteristics of the city and its emission sources. Noticeably, the impact of local meteorological conditions, Saharan dust outbreaks, and local phenomena as fires on UPII require further investigation and will be explored in ad hoc studies.

## 4 Conclusions

In this contribution, the daily-averaged concentrations of $PM_{10}$ and $PM_{2.5}$ measured in Rome (Italy) over the period 2018–2023 are analysed to evaluate the UPII. Since the correct selection of urban reference stations is still an open question, this study proposes and compares three different methods. These approaches are based on the identification of urban sub-sets of stations, according to the environmental classification provided by the monitoring network manager, namely "urban traffic", "urban background", and both.

The results show that the selection of urban stations mostly impacts $PM_{10}$ during winter, when the differences between the various approaches reach 100%, while for $PM_{2.5}$ differences remains below 20%. The outcomes suggest that, for the city of Rome, a better evaluation of UPII is achievable by considering the greatest number of stations available in the urban area, allowing us to consider the urban conformation and the peculiarities of the local emission sources.

The findings demonstrate that the choice of urban stations for the assessment of UPII is not naive and unambiguous, with practical implications on monitoring and treating human health, specific formulation of traffic plans, and tailored design of urban air quality improvement strategies. Furthermore, to properly study the UPII the local geographical characteristics, deployment of the stations, and emission sources have to be considered.

The results presented here will be further investigated by examining the correlation with local and synoptic meteorological conditions (which are responsible, for instance, for the advection of desert aerosol) and with UHII, to explain the physical interconnection between UPII and UHII.

**Acknowledgements** The authors gratefully acknowledge ARPA Lazio for providing air quality data.

**Author contributions** A.D.B: Conceptualization, Software, Validation, Formal analysis, Investigation, Resources, Data Curation, Writing - Original Draft, Writing - Review & Editing, Visualization, Funding acquisition, Project administration. M.E.: Software, Validation, Investigation, Data Curation, Writing - Review & Editing, Visualization. S.A.: Conceptualization, Formal analysis, Writing - Review & Editing, Funding acquisition. M.C.: Writing - Review & Editing. G.C.: Conceptualization, Formal analysis, Writing - Review & Editing, Funding acquisition. A.C.: Conceptualization, Writing - Review & Editing. S.F.: Conceptualization, Writing - Review & Editing. A.M.S.: Conceptualization, Formal analysis, Writing - Review & Editing.

**Funding** Open access funding provided by Università degli Studi di Roma La Sapienza within the CRUI-CARE Agreement. This study was supported by the PRIN 2022 “uRban hEat and pollution iSlands inTerAction in Rome and possible mitigation Strategies (RESTART)” project, funded by the Italian Ministry of University and Research (Prot. 2022KZ2AJE). Stefania Argentini and Giampietro Casasanta acknowledge the LIFE21-GIE-EL-LIFE “A System for Integrated EnviRonmental Information in Urban areaS (SIRIUS)” project. Serena Falasca gratefully acknowledges fellowship funding from MUR (Ministero dell’Università e della Ricerca) under PON “Ricerca e Innovazione” 2014–2020 (D.M. 1062/2021).
Open access funding provided by Università degli Studi di Roma La Sapienza within the CRUI-CARE Agreement.

**Data availability** The air quality dataset used in this study is freely available on the ARPA Lazio website (https://www.arpalazio.it/).

## Declarations

**Competing interests** The authors declare no competing interests.

## References

Barnaba F, Bolignano A, Di Liberto L, Morelli M, Lucarelli F, Nava S, Perrino C, Canepari S, Basart S, Costabile F, Dionisi D, Ciampichetti S, Sozzi R, Gobbi GP (2017) Desert dust contribution to PM10 loads in Italy: methods and recommendations addressing the relevant European Commission Guidelines in support to the Air Quality Directive 2008/50. Atmos Environ 161:288–305. https://doi.org/10.1016/j.atmosenv.2017.04.038

Cecilia A, Casasanta G, Petenko I, Conidi A, Argentini S (2023) Measuring the urban heat island of Rome through a dense weather station network and remote sensing imperviousness data. Urban Clim 47:101355. https://doi.org/10.1016/j.uclim.2022.101355

Crutzen PJ (2004) New directions: the growing urban heat and pollution island effect-impact on chemistry and climate. Atmos Environ 38(21):3539–3540. https://hdl.handle.net/11858/00-001M-0000-0014-8CA0-C

Di Bernardino A, Iannarelli AM, Casadio S, Perrino C, Barnaba F, Tofful L, Campanelli M, Di Liberto L, Mevi G, Siani AM, Cacciani M (2021) Impact of synoptic meteorological conditions on air quality in three different case studies in Rome, Italy. Atmos Pollut Res 12(4):76–88. https://doi.org/10.1016/j.apr.2021.02.01

Di Bernardino A, Mazzarella V, Pecci M, Casasanta G, Cacciani M, Ferretti R (2022) Interaction of the Sea Breeze with the Urban Area of Rome: WRF Mesoscale and WRF large-Eddy simulations compared to Ground-based observations. Bound-Layer Meteorol 185(3):333–363. https://doi.org/10.1007/s10546-022-00734-5

Jansson Å (2013) Reaching for a sustainable, resilient urban future using the lens of ecosystem services. Ecol Econ 86:285–291. https://doi.org/10.1016/j.ecolecon.2012.06.013

Li H, Zhou Y, Li X, Meng L, Wang X, Wu S, Sodoudi S (2018a) A new method to quantify surface urban heat island intensity. Sci Total Environ 624:262–272. https://doi.org/10.1016/j.scitotenv.2017.11.360

Li H et al (2018b) Interaction between urban heat island and urban pollution island during summer in Berlin. Sci Total Environ 636:818–828. https://doi.org/10.1016/j.scitotenv.2018.04.254

Li J, Zhou M, Lenschow DH, Cheng Z, Dou Y (2020a) Observed relationships between the urban heat island, urban pollution island, and downward longwave radiation in the Beijing area. Earth Space Sci 7(6), e2020EA001100. https://doi.org/10.1029/2020EA001100

Li H, Sodoudi S, Liu J, Tao W (2020b) Temporal variation of urban aerosol pollution island and its relationship with urban heat island. Atmos res 241:104957. https://doi.org/10.1016/j.atmosres.2020.104957

Mendez-Astudillo J, Caetano E, Pereyra-Castro K (2022) Synergy between the urban Heat Island and the urban Pollution Island in Mexico City during the dry season. Aerosol Air Qual Res 22(8):210278. https://doi.org/10.4209/aaqr.210278

Oke TR (1973) City size and the urban heat island. Atmos Environ 7(8):769–779. https://doi.org/10.1016/0004-6981(73)90140-6

Singh J, Payra S, Mishra MK, Verma S (2022) An analysis of particulate pollution using urban aerosol pollution island intensity over Delhi, India. Environ Monit Assess 194(12):874. https://doi.org/10.1007/s10661-022-10573-z

Tzavali A, Paravantis JP, Mihalakakou G, Fotiadi A, Stigka E (2015) Urban heat island intensity: a literature review. Fresenius Environ Bull 24(12b):4537–4554

UN (2018) Department of Economic and Social Affairs, Population Division: World Urbanization Prospects (WUP): The 2018 Revision, Methodology

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