TECHNICAL NOTE

A Mobile Vehicle-Based Methodology for Dynamic Microclimate Analysis

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Abstract

Accurate monitoring is critical for better understanding cities' microclimate conditions and safeguard citizens' health. Previous studies have performed microclimate analyses of urbanized areas by implementing data from either stable meteorological stations or satellites, or by developing mobile stations. Here, we present a vehicle-based monitoring campaign capable of monitoring both the scalar and directionally dependent variables that regulate the canopy layer environment. Under this framework, we performed a monitoring campaign within an Italian city, and measured simultaneously air temperature ($\pm 0.3^\circ\text{C}$ @ 20°C), relative humidity ($\pm 2\%$ @ 20°C), directional shortwave radiation (calibration uncertainty: $< 1.8\%$), CO_2 (± 50 ppm +2%) and PM_{10} ($< 1\%$) concentration, wind speed ($\pm 3\%$ @ 40 m/s) and direction ($\pm 3^\circ$ @ 40 m/s), and specific location (latitude, longitude and elevation). The presented assessment can be carried out within almost any area that motorized vehicles are allowed to access (e.g. through public transportation vehicles). Its application together with other mobile stations that can specifically assess also pedestrian areas, such as footpaths, urban parks, sidewalks and bike paths, as well as fixed meteorological stations and remote sensing techniques can contribute to a better understanding of microclimate patterns and hence to more efficient urban planning and risk assessments.

Article Highlights

- A novel methodology for monitoring urban environment is presented through transects.
- Advanced mobile drivable van-station is applied to a Mediterranean city in winter.
- Detailed intra-urban variations of urban microclimate variables are presented.
- Both scalar and directionally dependent microclimate variables are monitored.

Keywords Intra urban microclimate · Transect environmental monitoring · Mobile weather station · Anthropogenic heat · Urban resilience · Urban heat island

Introduction

Rural to urban population flow has increased dramatically within recent decades (Gao and O'Neill 2020). In 2016, over half of the world's population was reported to live in urbanized areas, while it is expected that the fraction will

be increased up to 85% by 2100 (Nations 2018). Urbanization results typically to high population and building density within cities which inevitably lead to substantial land-use and surface modifications (Liu et al. 2020). In turn, the local microclimate of the cities and the urban environment, in particular, are significantly affected. In fact, urban sprawl is responsible for unpleasant environments within cities and poses threats to human life (Santamouris 2013). For example, increased incidences for morbidity and mortality (Founda and Santamouris 2017), high greenhouse gas emissions (Duan et al. 2019; Keivani et al. 2020) and air pollution (Im et al. 2020; Skrynetska et al. 2018), increased energy consumption (Qiu and Kahn 2018; Abbasian and Souri 2019) and indoor/outdoor thermal discomfort (Li et al.

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2018), low water quality (Tortajada 2020) and incidences of energy poverty (Kousis et al. 2020b) among others are just few of urban sprawl's reported aftermaths.

Under this scenario, several studies have investigated urban microclimate modifications due to city expansion. Different techniques have been implemented for observing the profiles and evaluating the magnitude of various microclimate variables that regulate urban environment. Traditionally, in situ meteorological stations are utilized for measuring variables such as air temperature, humidity and so forth (Santamouris et al. 2007). However, in most cases, the meteorological stations are rather sparsely located and hence the outcomes represent a confined point-wise momentum of the measured variables and not their extended footprint. Remote sensing techniques have also been implemented by retrieving data from satellites, especially for land surface temperature (Zhou et al. 2018), but their low temporal resolution impedes their use for obtaining extensive and real-time intra-urban profiles of microclimate parameters. Therefore, for achieving higher spatial and temporal resolution, several studies have implemented mobile stations capable of monitoring various microclimate parameters (Kim et al. 2019).

In this paper, we present a vehicle-based methodology for intra-urban microclimate monitoring and analysis. Apart from scalar meteorological variables (e.g. temperature and humidity), directionally dependent variables such as shortwave radiation and illuminance can be directionally monitored as well with high accuracy, either the vehicle is in motion or not. We performed a monitoring campaign within the city of Perugia, Italy, which includes a medieval historical center (HCC), newly built residential areas developed near the main train station (UM1–UM2) and several suburban areas (GB1–GB2) that cover the biggest area of the city. The followed path of the monitoring campaign covered all these areas. Here, we demonstrate the outcomes of the monitoring campaign concerning air temperature and absolute humidity as scalar variables and shortwave radiation as vectorial variable. Both are critical determinants of the outdoor urban environment and highly affect citizens' well-being. For example, high outdoor inner-city temperature is a primary indicator of outdoor discomfort that may put citizens' health in serious danger (Santamouris 2013). Similarly, absolute humidity is lately regarded from epidemiologist as an indicator of influenza virus, e.g. COVID-19, related transmission levels (Rashed et al. 2020). Moreover, CO₂ and PM10 concentrations, averaged shortwave radiation, wind speed, air pressure and dew-point temperature profiles across the following pathway are presented at a local zone-scale, i.e. green belt, urban modern and historical city center, and correlated accordingly for identifying possible primary relationships through distance covariance.

Methods

The mobile monitoring station reported here can measure simultaneously air temperature (accuracy: ± 0.3 °C @ 20 °C), relative humidity ($\pm 2\%$ @ 20 °C), shortwave radiation (spectral range: 285–3000 nm, calibration uncertainty: $< 1.8\%$), illuminance (range: 0–10,000 lx), dewpoint temperature, CO₂ (range: 0–2000 ppm, accuracy: ± 50 ppm +2% of measured value) and PM10 (resolution: 1/4096, accuracy: $< 1\%$) concentration, and speed (accuracy: $\pm 3\%$ @ 40 m/s, resolution: 0.001 m/s) and direction (Accuracy: $\pm 3^\circ$ @ 40 m/s, resolution: 1°) of wind (Kousis et al. 2021). All sensors are calibrated and placed on five specifically designed hosting-units. All units are positioned on the two façades of the vehicle, i.e. on the top and the back sides to minimize shadowing effects (Fig. 1).

Shortwave radiation and illuminance are measured each by five different sensors oriented towards (1) the sky, (2) the street, the (3) right, the (4) left and the (5) backside of the vehicle. Since, however, the presented monitoring campaign was carried out during daytime, measurements of illuminance are not presented herein. Air temperature is measured by five different sensors, each placed in each unit and subsequently a mean value is calculated. In addition, data concerning the specific position, i.e. longitude, latitude and altitude, of the station were obtained by a Global Position System embedded in the sensor of wind speed and direction for correcting direction misalignments due to the vehicle's motion.

We mapped out a monitoring path within the city of Perugia, Italy. According to the Koppen and Geiger classification (Beck et al. 2018), Perugia is classified as Cfa and is characterized by humid subtropical climate conditions. The pathway is almost circular and it ends where it starts. It passes through different types of urban morphology, land-use, and human activity. Therefore, we divided the path to sub-areas according to their particular characteristics. We identified three different sub-zones within the city, i.e. the main suburb area of Perugia, the recent urban neighbourhood close to the main train station and the center area of the city. Afterwards, we performed monitoring campaigns during the winter period of 2020. Subsequently, we reckoned the averaged January and averaged Winter day profiles with data retrieved from the meteorological station of the University of Perugia, located in close proximity to the starting/ending point of the monitoring campaign. (Kousis et al. 2020a). Here, we present the outcomes of a day-time monitoring campaign, carried out on 20th of January, since the difference among the temperature profile of this day and the profiles of the averaged January and averaged Winter days were found be statistically insignificant (p -value > 0.05) (Table 1),

Fig. 1 The presented mobile monitoring station **Table 1** Wilcoxon test among the day of the presented monitoring, and the averaged January and Winter days of the same year

	January day (averaged)			Winter day (averaged)		
	<i>p</i> -val	Eff. size	$\Delta T_{\max}$	<i>p</i> -val	eff. size	$\Delta T_{\max}$
20/01/2020	0.36	0.187	– 0.6	0.84	0.254	– 0.9

$$\Delta T_{\max} = T_{20/01/2020} - T_{\text{January/Winter day}}$$

with respect to Wilcoxon matched-pairs signed rank test (Bagkavos and Patil 2021). Therefore, we considered this day as a typical winter day. Moreover, this day was also characterized by clear sky conditions and relatively stable boundary conditions, e.g. low wind speed and ambient temperature variation. The monitoring campaign started at 12:38 and finished at 13:50.

All measurements are taken at the same time-stamp every 10 s. We ensured accurate measurements of air temperature by aspirating the corresponding sensors by vehicle's motion, and by positioning them inside a specifically designed radiation shield. Nevertheless, vehicle's speed affects intrinsically the accuracy of mobile measurements. Oke et al. (2017) recommends a vehicle speed around 10 km/h. At the same time, according to Taha et al. (2018), data obtained on vehicle speed below 10 km/h should be discarded, for minimizing the effects of anthropogenic heating changes. Several relevant studies report vehicle speed higher than 30 km/h (Hart and Sailor 2009; Soltani and Sharifi 2017; Jacobs et al. 2019). Here, to obtain high spatial resolution, we maintained vehicle's speed constantly around 20 km/h and hence the

measurements of all variables were taken approximately every 50 m. Another limitation that mobile monitoring is typically prone to is the need of applying correction methods to the parameters that may be affected by the variation of weather boundaries due to time-elapsing, especially when the duration of the campaign is well above 1 h (Taha et al. 2018). Here, no time-correction method was applied. Instead, to minimize the time-dependency of the data, the present monitoring campaign was systematized to last approximately one hour and performed under rather stable boundary meteo-conditions, i.e. the maximum air temperature range measured by the meteorological station of the University of Perugia during the campaign was 0.2 °C and the corresponding standard deviation was 0.05 °C, while the wind speed was almost always well below 10 m/s. Effects on the data owing to traffic, shadowing and other unforeseen random events that may occur due to the contingent nature of urban areas are also possible. If apparent, however, their magnitude could be evaluated and if needed mitigated, by selecting a proper scale-analysis, e.g. a neighbourhood-scale assessment.

Table 2 Difference of the mean temperature values in-between the defined zones (measured by the mobile station) and the simultaneous mean values measured by the meteorological station of the University of Perugia

	GB1	UM1	HCC	UM2	GB2
$\Delta T = T_{\text{mobile}} - T_{\text{fixed}}$	0.1 °C	0.0 °C	−0.9 °C	0.2 °C	0.3 °C

Results

Figure 2 illustrates the profiles of air temperature and absolute humidity recorded by the presented monitoring station together with the air temperature measured by the

meteorological station of University of Perugia (Fig. 2a), a corresponding map representation wherein color represents the temperature and size the absolute humidity (Fig. 2b) and a directional representation of Shortwave radiation at specific spots across the followed pathway (Fig. 2c). A first understanding concerning the spatial tendency of both selected variables can be derived from Fig. 2b. Overall, the city center was found a bit cooler than the adjacent areas. The lowest value of temperature was recorded within the HCC (7.6 °C) while the highest was recorded in the GB2 (9.5 °C). On the other hand, the profile of absolute humidity is characterized by rather small deviations (standard deviation = $\pm 0.1 \text{ g/m}^3$). This

Fig. 2 **a** Air temperature and absolute humidity profiles, **b** pathway of the monitoring campaign and spatial distribution of air temperature and absolute humidity, **c** directional distribution of Shortwave radiation in w/m^2

is also evident in Fig. 2a. However, a small drop can be seen as entering to the city center, which is likely due to the absence of greenery or water surfaces. Moreover, the decrease (up to 1.6 °C) and rise (up to 1.9 °C) of air temperature as getting in and out, respectively, from the historical center is also evident. This variation experienced within the same city (less than 3 km as the crow flies) cannot be captured by a unique fixed meteorological station, as the one here presented as reference and located at the monitoring route starting/ending point (Fig. 2b). Indeed, mean temperature gaps of 0.1 °C, −0.9 °C, 0.2 °C and 0.3 °C are observed for the crossed areas with respect to the reference (GB1, HCC, UM2 and GB2 areas, respectively) (Table 2). This indicates a possible inability of fixed meteorological stations to capture intra-urban variabilities, that is strictly related to the specific position of the station. For instance, no certified meteorological station is reported within the center area of Perugia. A fine-grain fix stations network would be needed to catch the observed intra-urban variability which is an expensive solution from different perspectives (sensors purchase, installation, and maintenance costs of a large number of weather stations). The application of mobile monitoring

techniques may not only offer insights to such variations, but also identify key-locations and the optimum number for the strategic development of fixed stations, and further support intra-urban monitoring being complementary to long-term fix monitoring.

The HCC of Perugia is surrounded by medieval walls and is characterized by narrow and well-shaded streets. Most of these areas are not accessible to motorised vehicles. Hence, incident shortwave radiation can be significantly lower as compared to the GB1–GB2 and UM1–UM2 areas which are characterized by wider open air spaces. In fact, as it can be seen in Fig. 2c, the distribution of shortwave radiation may substantially vary within the very same city in terms of both inner-city location and direction. For instance, at spots A and B located within the open-air areas of the GB1 and near to UM1 respectively the vertical incident short-wave radiation dominates other, while at the well-shaded spot C the highest fraction of incident shortwave radiation comes from rightward. Similarly, depending on the specific location within the city significant portion of shortwave radiation may come from the left (spot A) or right side of the specifically monitored canyon (spots B, D, E).

Fig. 3 **a** CO₂ concentration in ppm, **b** PM10 concentration in ppm, **c** average shortwave radiation w/m², **d** wind speed in m/s, **e** air pressure in Pa, **f** dew-point temperature in °C, **g** distance covariance coefficients, scatter plot and 2D Kernel density estimation in between the measured variables. *T* is temperature, *AH* is absolute humidity, *SR* is averaged shortwave radiation and *WS* is wind speed

Figures 3, 4, and 5 illustrate the point-wise footprints of CO₂ concentration (a), PM10 concentration (b), averaged shortwave radiation (c), wind speed (d), air pressure (e) and dew-point temperature (f), as well as the outcomes of the distance covariance applied to the measured parameters (g) across the the GB, UM and HCC areas, respectively. The highest vales of shortwave radiation and wind speed were recorded within the suburb area owing to the large open-air areas. On the other hand, the highest values of CO₂ and PM10 were recorded within the area close to the train station, which is typically characterised by high vehicular traffic and anthropogenic action during the day-time, as compared to the other city zones. Overall, the city center is characterised with the lowest values of almost all the monitored parameters, most likely due to the shadowed narrow streets, that are well covered by the high and circular medieval walls and the limited vehicular traffic as compared to the other city-zones. Furthermore, the primary relationships among the measured parameters within each sub-area were assessed through distance covariance (Székely and Rizzo 2013). The corresponding coefficients (r) are displayed in blue when p value ≤ 0.05 and are considered statistically significant, and in grey when p value $>$

0.05 and considered statistically insignificant. The diagonal comprises the rug plots, the part above the diagonal comprises the scatter plots and the part below the diagonal comprises contours of a 2D Kernel density estimation. The resulted coefficients are low to moderate, i.e. they range from 0.11 to 0.62. The most significant relationships were found between CO₂ concentration and shortwave radiation within the center area ($r = 0.62$, p value < 0.05) and train area ($r = 0.50$, p value < 0.05).

Discussion and Future Outlook

Urbanization has gradually become a critical issue of environmental degradation that poses a great challenge to social development, citizens' well-being and cities as an ecological niche. The increasing population density and the corresponding demands lead to natural-to-urban land alterations that modify the patterns of the microclimate parameters of urban environments (Yun et al. 2020). Urban and urbanized areas are prone to local energy balance modifications that in turn affect outdoor and indoor conditions and hence the citizens' life quality. For instance, excessively high ambient

Fig. 4 **a** CO₂ concentration in ppm, **b** PM10 concentration in ppm, **c** average shortwave radiation w/m², **d** wind speed in m/s, **e** air pressure in Pa, **f** dew-point temperature in °C, **g** distance covariance coefficients, scatter plot and 2D Kernel density estimation in between the measured variables. T is temperature, AH is absolute humidity, SR is averaged shortwave radiation and WS is wind speed

Fig. 5 **a** CO₂ concentration in ppm, **b** PM₁₀ concentration in ppm, **c** average shortwave radiation w/m², **d** wind speed in m/s, **e** air pressure in Pa, **f** dew-point temperature in °C, **g** distance covariance coefficients, scatter plot and 2D Kernel density estimation in between the measured variables. *T* is temperature, *AH* is absolute humidity, *SR* is averaged shortwave radiation and *WS* is wind speed

and surface temperatures, i.e. Urban Heat Island (UHI) effect (Kousis and Pisello 2020), are reported during the summer period in hundreds of cities. UHI, together with the shortage of green and water surfaces, alters the fluxes of turbulent sensible and latent heat, as well as humidity profiles (Arnfield 2003). Wind and ambient pressure profiles are also altered due to lack of efficient urban planning (Grawe et al. 2013), which, furthermore, in many cases turn carbon sinks to carbon sources (Han et al. 2017). In addition, anthropogenic activity such as public and private transportation, working needs and spaces, result in exacerbated energy consumption, air impairment, hazardous wastes, and carbon emissions (Boehme et al. 2015). In fact, according to UN habitat, even though urban areas cover approximately 2% of Earth's surface, they account for 78% of the world's energy consumption and are responsible for more than 60% of greenhouse gas emissions (Habitat 2013). At the same time, in 2016, the World Health Organization reported that 91% of the world population is exposed to air pollution incidences (WHO 2016). The effects of urbanization are usually interconnected and if not addressed accordingly can seriously threaten environmental health. For instance, high ambient temperatures are found to increase morbidity, mortality (Tan et al. 2010) and energy poverty incidences (Kousis

et al. 2020b), while exposure to high concentration of particulate matter can also pose serious threat to citizens' well-being and health, e.g stroke, heart disease, lung cancer, and chronic or acute respiratory diseases (Stockfelt et al. 2017; Raaschou-Nielsen et al. 2013).

An in-depth evaluation of the parameters that regulate urban environment and hence safeguard urban environmental health and sustainability need to be undertaken under a multidisciplinary approach and improved methods of health risk assessment. Static observation stations provide a substantial information with respect to environmental parameters at meso and global scale. Yet, a more sophisticated investigation at the micro-scale is needed for efficiently evaluating the intra-urban characteristics of a city that are typically characterized by significant heterogeneity and structural complexity. Under this framework, here, we present a vehicle-based methodology for monitoring and representing the intra-urban variations of the main microclimate parameters within the urban canopy, by simultaneously monitoring both scalar and directionally dependent variables with high spatial resolution. The present methodology can be applied to almost any urban area, since all the monitoring components utilised here can be easily re-attached to almost any other similar configuration. The acquisition of

the specific vehicle speed during the monitoring campaign, as well as the design of elapsed time-correction protocols when the duration of the campaign is well above one hour should be considered as a crucial future outlook for improving the reliability and accuracy of the measurements. In addition, future research should optimise the monitoring path design with respect to the specific land use/land cover and overall urban planning of the investigated city. Intra-urban patterns of the microclimate parameters should be further assessed under both seasonal and annual scales and exploited under geographic information system framework. Under this scenario, we believe that a holistic approach that comprises data collected by the presented methodology and data collected from other mobile micro-scale stations, such as helmets (Pigliautile and Pisello 2018), trolleys (Vasilikou and Nikolopoulou 2020) and carts (Middel and Krayenhoff 2019) in conjunction with stable stations and satellite data, will exploit the understanding of the urban microclimate and the corresponding environmental quality with respect to the specific local morphology, anthropogenic action, urban planning and temporal weather conditions.

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