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Drone-assisted infrared thermography for calibration of outdoor microclimate simulation models

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ABSTRACT

Outdoor microclimate modelling is getting popular for estimating comfort conditions in urban environments. Current calibration approaches usually rely on measurements of air temperature for a limited number of points in the study domain, in spite of the fact that it is the Mean Radiant Temperature (Tmrt) the parameter mostly affecting comfort. However, the direct measurement of Tmrt outdoors via the globe thermometer or using the six direction radiation method is prone to errors.

To overcome these issues, the present paper proposes a novel method to indirectly improve its estimate based on the use of infrared thermal pictures gathered by drone flights to measure surface temperatures, and then use these values for calibrating numerical models. This novel approach has been demonstrated for a $400 \times 400\ m^2$ wide area in the city of Medicina (Italy) and showed a good agreement with ENVI-met simulations, with average and standard deviation values difference between measured and simulated surface temperatures of 1.53 °C and 2.22 °C respectively. The highest differences (up to 19 °C) are found for areas densely covered by vegetation. Further studies are planned to evaluate the goodness of the calibration pixel wise and to propose calibration thresholds based on Tmrt sensitivity.

1. Introduction

The determination of outdoor comfort conditions for humans represents a major factor to quantitatively assess the quality of urban microclimate and drive the design of urban settlements (Coccolo et al., 2016). Despite the relevance of the topic, and the presence of established thermal comfort theories concerning indoor spaces such as Fanger's Predicted Mean Vote (Fanger et al., 1970) and the adaptive approach (Nicol & Humphreys, 2002), the problem of founding a solid outdoor comfort theory is yet to be solved. This is mainly due to the extreme variability over time of weather variables such as solar radiation and wind velocity, which is intertwined with urban morphology and materials used and may lead to additional phenomena like the Urban Heat Island (UHI) effect (Andreou, 2013; Evola et al., 2017; Gagliano et al., 2015).

Nonetheless, various outdoor comfort indices have been proposed so far, which according to Coccolo's et al. classification (Coccolo et al., 2016) may be classified into thermal indices (e.g Physiologically Equivalent Temperature, Perceived Temperature, Universal Thermal Climate Index), empirical indices (e.g. Actual Sensation Vote, Thermal Sensation Vote) and indices based on linear equations (e.g. Discomfort Index, Effective Temperature).

When it comes to estimate such indices, it is of paramount importance to correctly evaluate the Mean Radiant Temperature (Tmrt), which syntethizes the complex shortwave and longwave radiant exchange of a person in a given body posture and clothing – and within a given environment – in one temperature dimension index (Kántor & Unger, 2011). Being defined as *"the uniform temperature of an imaginary enclosure in which the radiant heat transfer from the human body equals the radiant heat transfer in the actual non-uniform enclosure"* (ASHRAE, 2001), its determination via experimental measurements proved to be challenging if using either the globe thermometer (both traditional black and grey versions) or the six direction radiation method (Chen et al., 2014; Kántor & Unger, 2011; Thorsson et al., 2006).

On the other hand, simulation tools such as CitySim Pro, ENVI-met, RayMan, Ladybug, Autodesk CFD and SOLWEIG can be used for estimating Tmrt with a varying degree of accuracy depending on software limitations and complexity of the urban landscape (Coccolo et al., 2017; Elwy et al., 2018). No matter the tool employed, the radiant heat exchange due to direct sun and sky heat exchange can easily account up to a third of the variability in the calculation of a comfort index such as the UTCI (Mackey et al., 2017). The same referenced study derived a

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hierarchy of critical variables for outdoor comfort modelling, namely sky heat exchange, wind patterns and surface temperature in order of relevance. The first and the last directly impacts on the calculation of the Tmrt, but they are seldom used for calibrating outdoor comfort models, the current practice being that of calibrating against punctual air temperature measurements. Moving from these premises, this paper proposes a novel method that overcomes such limitations through the use of infrared thermal pictures gathered by drones for the measurement of surface temperatures of big spatial domains. The method has been demonstrated against simulations carried out in ENVI-met, which is the most used tool for outdoor microclimate studies as detailed in the following section.

2. Review of different approaches to outdoor microclimate simulations in ENVI-met

It is possible to find an increasing body of research in the literature using ENVI-met outdoor microclimate simulations. In fact, the software is largely used at different scales of investigation: Giridharan and Emmanuel (2018) reported on the use of the tool for assessing the impact of urban compactness on the Urban Heat Island (UHI) effect in tropical countries (large scale and urban pianification), while Kleerekoper et al. did the same considering also different urban layouts under temperate climate conditions (Kleerekoper et al., 2017). Smaller scales – from neighborhood or district area to squares or urban canyon – are instead more frequently concerned with the issue of measuring different pavements and greenery thermophysic parameters such as albedo and leaf evapotranspiration rate, or specific urban layouts like courtyards. As an example, Koutra et al. (Koutra et al., 2018) reviewed various ENVI-met simulations coupled with on-site measurement campaigns, most often recording air temperature and relative humidity and less frequently mean radiant temperature and wind speed, especially when the aim of the research is to determine outdoor comfort conditions. A very recent review of mitigating strategies of Lai et al. (Lai et al., 2019) reports methods to measure and simulate urban thermal environmental parameters, the effect of building geometry along with shading from trees, and a literature about various mitigation strategies to reduce either the air temperature or the Physiologic Equivalent Temperature (PET).

In all these researches, simulation results are not always calibrated (or the model validated) against on-site measured data, thus reducing the reliability of the simulation outcomes. In the following, a systematic review of different simulation approaches followed by scholars when dealing with ENVI-met simulations is presented. In order to account for the larger number of relevant papers as possible, the Scopus website was browsed using the following keywords: “ENVI-met + validation”, “ENVI-met + calibration”, “ENVI-met + measure” or “ + monitoring”.

2.1. With on-site measurements but without calibration

The first kind of research approach with ENVI-met simulations can be categorized as with on-site measurements but without calibration or comparison between measured and simulated data. These researches focused on ENVI-met equations and/or results of simulation scenarios, and in some cases refer to a single physical variable (e.g. the mean radiant temperature). The literature is wide, and only the most significative examples are reported for the sake of brevity. Ahn et al. (2018) analyzed simulated and measured data concerning Tmrt in order to study the effect of shade on pedestrian comfort in a urban canyon. Buccolieri et al. (2018) instead reported on the relationship between greenery amount, thermal comfort and air quality in terms of PM_{10} concentrations, according to different scenarios of green covery ratio, shrub covery ratio and ecological landscaping plot ratio, but without any use of experimental data for calibration purposes. Similarly, in the work of Ma et al. (2019), ENVI-met simulations concerning different tree design options are commented but none of these has been validated against on-site measurements of thermal quantities because a comparison is carried out against pollution concentration values. Indeed, the paper reports on the measurement of PM_1, $PM_{2.5}$, PM_4, PM_{10} and TSP through the use of New Star Environmen- tal's MetOne 831 Mass Monitor at a height of 1.5 m above the ground at one hourly time step.

A similar approach has been followed in a recent research of Battista, de Lieto Vollaro and Zinzi (Battista, de Lieto Vollaro, & Zinzi, 2019) about the UHI effect in a neighbourhood in Rome aimed at showing the effects of several scenarios on outdoor comfort without any calibration of the simulations. Also Sözen and Koçlar Oral (Sözen & Koçlar Oral, 2019) compared ENVI-met results of several simulations concerning different urban canyons and courtyards orientation in Madrid but again without reporting on any on-site measurement or calibration process.

Finally, another research stream focused on the effects of specific thermo-physical parameters such as ground reflectance (Azam et al., 2018), green materials (Berardi, 2016) and different albedo values of pavements (Rosso et al., 2016), on outdoor microclimate.

2.2. With on-site measurements and calibration

The researches employing measurements for calibration purposes, for just one or several points in a spatial domain, are found to mainly adopt two calibration strategies:

- by *statistical analysis* of measured and simulated data, for one or more variables (in most cases the statistical analysis concerns air temperature only);
- by *trends comparison*: one or more measured variables trends are graphically compared with simulation results (again air temperature is the most frequently assessed variable).

The statistical analysis usually makes use of at least one of the following indexes:

- the coefficient of determination (R^2), expressed by the following equation:

$$R^2 = \frac{\sum_{i=1}^{n} (S_i - \bar{M})^2}{\sum_{i=1}^{n} (M_i - \bar{M})^2} \tag{1}$$

the Root Mean Square Deviation (RMSD), or Root Mean Square Error (RMSE), by formula:

$$RMSE = \sqrt{\left(\frac{\sum_{i=1}^{n} (M_i - S_i)^2}{N_i}\right)} \tag{2}$$

the Mean Bias Error (MBE):

$$MBE = \frac{\sum_{i=1}^{n} (M_i - S_i)}{\sum_{i=1}^{n} M_i} \tag{3}$$

the Wilmott’s index of agreement (d):

$$d = 1 - \left(\frac{\sum_{i=1}^{n} (M_i - S_i)^2}{\sum_{i=1}^{n} (|S_i - \bar{M}| + |M_i - \bar{M}|)^2}\right) \tag{4}$$

the Mean Absolute Error (MAE):

$$MAE = \frac{1}{N} \sum_{i=1}^{N} |S_i - M_i| \tag{5}$$

the Mean Absolute Percentage Error (MAPE):

$$MAPE = \frac{1}{N} \sum_{i=1}^{N} |S_i - M_i| \cdot 100 \tag{6}$$

- Pearson’s coefficient: