



Directional mean radiant temperature decomposition reveals micro-scale drivers of urban heat stress in Novi Sad (Serbia)

Maaïke van der Veld^a, Gert-Jan Steeneveld^a, Stevan Savić^b, Jelena Dunjić^b, Daniela Arsenović^b, Dragan Milošević^{a,c,*}

^a Meteorology and Air Quality Section, Wageningen University, P.O. Box 47, 6700 AA Wageningen, the Netherlands

^b Faculty of Sciences, University of Novi Sad, Trg Dositeja Obradovića 3, Novi Sad 21000, Serbia

^c Hydrology and Environmental Hydraulics Section, Wageningen University, P.O. Box 47, 6700 AA Wageningen, the Netherlands

ARTICLE INFO

Keywords:

Mean radiant temperature
Physiological equivalent temperature
Directional radiation fluxes
Sky view factor
Heat stress
Micrometeorological measurements

ABSTRACT

Urban heat stress is an increasing issue with large implications for health and comfort. This study investigates micro-scale drivers of heat stress in Novi Sad, Serbia, using mobile meteorological carts to obtain measurements at 29 locations with diverse urban design during a hot, cloud-free summer day. Air temperature, relative humidity, wind speed and six-directional short- and longwave radiation were recorded and used to compute Mean Radiant Temperature (MRT) and Physiological Equivalent Temperature (PET). PET values ranged from 25 °C to 56 °C, indicating slight to extreme heat stress. Sensitivity analysis showed MRT as the dominant driver of spatial differences in PET during daytime. Decomposition of radiant load revealed that longwave lateral radiation contributed most to radiant load, but lateral shortwave contributions were most variable, because of the variability in local shading. Sky View Factor (SVF) appeared a strong predictor of MRT and PET, with a 10% reduction in SVF lowering MRT up to 5 °C. In contrast, surface type (grass vs. impervious) had only minor effects, limited to reduced upward longwave radiation in the afternoon and evening. Buildings and trees achieved comparable maximum MRT reductions, though tree-induced shading exhibited greater variability. These results show the importance of directional radiant load decomposition for identifying which radiative pathways contribute most to heat stress and when. By distinguishing the dominant solar and longwave components—and their dependence on SVF, shading type, and surface materials—this approach provides site-specific empirical evidence on the radiative mechanisms that shaped pedestrian heat stress under clear-sky, low-wind conditions in a temperate climate city.

1. Introduction

More than half of the world population lives in cities, and this is expected to keep rising (United Nations Department of Economic & Social Affairs, 2019). One of the challenges urban areas face is the urban heat island, which is the effect that canyon layer air temperatures in urban areas are higher than their rural surroundings (Oke et al., 2017). This is caused by differences in surface properties and geometry, Sky View Factor (SVF), wind blocking, soil composition and moisture, and emission of heat and air pollution in urban areas. These effects combined with urbanization and climate change lead to an increase in dangerous heat stress conditions in urban areas (Chapman et al., 2017).

Heat stress has a large impact on well-being and mortality, especially of already vulnerable groups (Nazarian et al., 2022). Next to that, urban

overheating increases energy consumption and lowers air quality (Santamouris, 2020). Heat stress is especially detrimental for population in low-income and developing countries. Among the developing countries, Serbia has seen an increasing impact of heat stress on urban health. Arsenović et al. (2023) have shown that high summer temperatures increase mortality rates in five cities in Serbia (Belgrade, Novi Sad, Niš, Loznica, and Vranje). Long intense warm periods and sudden day-to-day changes in summer temperatures have also been linked to an increase in hospital admissions in Novi Sad (Savić et al., 2023). Urban human biometeorology, the study of the influence of weather and climate on humans, is a growing field of research (Hondula et al., 2017) as it is crucial to find drivers of heat stress in different climates and at different times of the day, especially in low-, middle-income and developing countries.

* Corresponding author at: Meteorology and Air Quality Section & Hydrology and Environmental Hydraulics Section, Wageningen University, the Netherlands.
E-mail address: dragan.milosevic@wur.nl (D. Milošević).

<https://doi.org/10.1016/j.scs.2026.107717>

Received 5 January 2026; Received in revised form 16 July 2026; Accepted 17 July 2026

Available online 20 July 2026

2210-6707/© 2026 The Author(s). Published by Elsevier Ltd. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>).

Heat stress, as integral part of human biometeorological studies, has been quantified and analysed using different indices. Most indices use multiple or all four of the important biometeorological factors: air temperature (T_a), Mean Radiant Temperature (MRT), relative humidity (RH) and wind speed (Oke et al., 2017). One of these indices is the Physiological Equivalent Temperature (PET), which combines the four meteorological variables with factors of the human body, such as the metabolic rate and clothing factor (Höppe, 1999). The PET is a useful variable, as it quantifies thermal comfort well in different climates and is straightforward to interpret (Matzarakis et al., 1999). The PET uses MRT as a measure of the total radiation absorbed by the human body. MRT is defined as the temperature that a uniform surrounding would need to have to have the same radiative impact as the actual surrounding (ISO, 1998).

Radiation is often dominating spatial differences in heat stress during daytime warm conditions, as shown by previous studies using biometeorological stations. Aleksandrowicz and Pearlmutter (2023) found that the R^2 of the relationship between MRT and PET was 0.92, much higher than T_a which had an R^2 of 0.11. Lee et al. (2013) found that MRT explained 89% of variation in PET during daytime, but during nighttime T_a was the most important variable explaining 89% of variation, while MRT explained 62%. Middel and Krayenhoff (2019) found that MRT explained 90% of PET variability and 70% of variability in another thermal comfort index, the Universal Thermal Climate Index (UTCI). These studies show that understanding the variability in MRT is of great importance to understand heat stress.

Because of the importance of MRT for heat stress, shading has been found as a very effective cooling strategy. Sangman et al. (2025) found that a single tree reduced PET by 6.3 °C to 8.3 °C depending on the species, mainly by a reduction in MRT. Kántor et al. (2016) found that a tree reduced PET by 9.3 °C and MRT by 22.1 °C. Middel and Krayenhoff (2019) found that trees even lowered the MRT by 4.0 °C for 10% of canopy cover added during a heatwave in Phoenix, Arizona. Shading by trees and buildings is often found to result in similar reductions in MRT at the same SVF (Colter et al., 2019; Middel et al., 2016). Du et al. (2020) and Middel and Krayenhoff (2019) found that trees had a lower emittance of longwave radiation compared to urban structures, but Du et al. (2020) also found that trees transmitted more solar radiation. Buildings can also have negative effects on the perceived temperature, for example by restricting airflow (Wang et al., 2025). Some processes also differ during different parts of the day. During nighttime, for example, dense tree canopies can increase heat stress by trapping the heat of the day (Wujeska-Klaue & Pfautsch, 2020) and emitting longwave radiation (Coutts et al., 2016; Middel & Krayenhoff, 2019). Grass surfaces have also shown to lower the MRT compared to impervious ground covers (Lindberg et al., 2016; Middel & Krayenhoff, 2019). However, the effect of surfaces has been shown to be complex and differs at different temperatures (Fang et al., 2024; Middel et al., 2020).

MRT can be measured in multiple ways; using six-directional shortwave and longwave radiation measurements, but also with a globe thermometer. A globe thermometer is more affordable and provides a decent estimate of the MRT, but the performance strongly declines under conditions with high wind speed or incoming solar radiation (Fang et al., 2023; Liu et al., 2022; Thorsson et al., 2007). Globe thermometers also do not provide insight into the directional radiation fluxes, which limits understanding of how the individual radiative pathways shape human heat exposure. For these reasons, globe thermometers are not the best option under the abovementioned conditions and when insights into radiative pathways are desired. Insights in the radiative pathways can be gathered using a 3-dimensional approach, such as infra-red thermography, such as by Lamberti et al. (2025) or six directional radiation flux measurements. However, this type of research is technically demanding based on complexity of the instruments, financially challenging in terms of acquiring this technology and having enough human resources for field measurements and is thus rarely implemented in heat stress research (Li et al., 2022).

Nevertheless, six-directional radiation flux measurements have been sporadically used for biometeorological campaigns in several cities. Several of those studies do not have the main focus on radiation fluxes and use it to provide a highly accurate estimate of MRT, without analysing the fluxes separately (Aleksandrowicz & Pearlmutter, 2023; He et al., 2020; Klemm et al., 2015; Kousis et al., 2021; Steeneveld et al., 2014). Other studies do focus on the separate fluxes using stationary measurements at a limited number of locations (Ali-Toudert & Mayer, 2007; Du et al., 2020; Fang et al., 2023; Kántor et al., 2016, 2018). Those studies provide great insight into the diurnal cycle of the variables but have limited information on spatial variability. Most studies using mobile measurements focus solely on daytime conditions (Aviv et al., 2021; Holst & Mayer, 2011; Lai et al., 2018; Lee et al., 2014). However, evening and nighttime heat is associated with adverse health effects and mortality (He et al., 2022). Mobile measurements using measurements outside of the window 8:00 to 18:00 are very scarce (Lee et al., 2013; Middel & Krayenhoff, 2019). Notably, decomposition of the total radiant load or MRT into the different fluxes to examine their relative contributions, has – from all the aforementioned studies – only been performed by Middel and Krayenhoff (2019). Their study focusses on the extreme heat in Arizona, so those results might not transfer to other climatic zones. In Pisa, Italy, a relevant study has been performed, where the authors divided absorbed radiation into longwave radiation and diffuse and direct solar radiation and analysed the directionality of the fluxes, using a different measurement set-up (Lamberti et al., 2026). Their aim was to develop an alternative for globe thermometers using a cylinder, to achieve a simple and reliable MRT estimation. This study also provides excellent insight in the exposure of the human body to different types of radiation. However, since it was out of their scope, this study did not provide insight in differences between different locations.

To summarize, the complete link from location characteristics to radiative pathways, to MRT to heat stress has only been examined in few studies. Consequently, it is still unclear: (i) which directional radiation components (shortwave vs longwave; vertical vs lateral) control MRT and heat stress at different times of day across diverse urban locations, most importantly after sundown, and (ii) to what extent simple, transferable urban descriptors—most notably SVF as a proxy for obstruction by trees and buildings, and pervious versus impervious ground cover—explain the spatial variability in heat stress in temperate climates. To address this gap, we deploy Mobile Micrometeorological Carts (MMCs) to measure air temperature, humidity, wind speed and six-directional radiation across diverse urban micro-environments in Novi Sad, Serbia during a heatwave, and we quantify how the relative importance of meteorological variables, directional radiation components, SVF and ground cover governs MRT and heat stress over four parts of the day (from morning to evening). The aim is to uncover and quantify the complete link from location characteristics to radiative pathways, to MRT, to heat stress. The Novi Sad context provides the empirical basis, but the findings speak to temperate urban climates more broadly. By explicitly linking urban form and surface characteristics to human thermal exposure under extreme heat, this study delivers evidence-based insights to support heat-mitigation strategies, safeguard vulnerable populations, and help advance the design of more climate-resilient and socially sustainable temperate European cities.

2. Methods

2.1. Study area

The field micrometeorological measurements have been performed in Novi Sad, Serbia (Fig. 1). It is the second largest city in Serbia with a population of 325.000 (Milošević et al., 2023). It is located in the Northern part of Serbia on the Pannonian Plain (80–86 m a.s.l.). The Danube and the Danube-Tisa-Danube Canal flow through the city. Novi Sad has a temperate oceanic climate (Cfb) (Kottke et al., 2006) with average monthly 2-m T_a ranging from -0.3 °C in January to 21.8 °C in

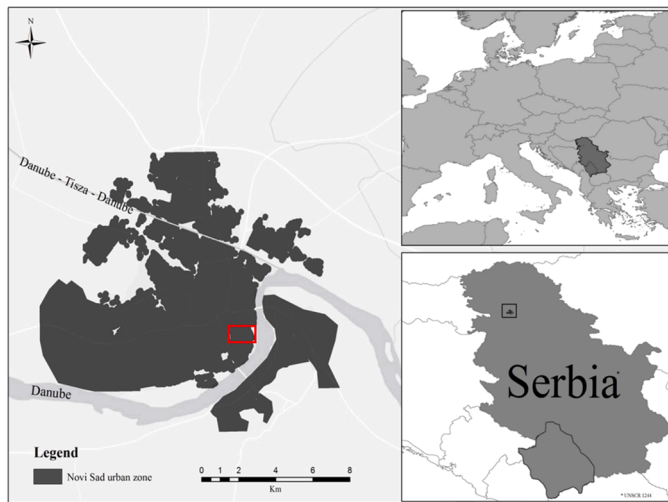


Fig. 1. Location of study area in Novi Sad (red box) & of Novi Sad in Serbia & Europe (adapted from Dunjić et al., 2021).

July (Milosević et al., 2023). The mean annual precipitation amounts 623 mm. The study area can be described using the Local Climate Zone (LCZ) classification system, which is used as a framework in urban climate research (Stewart & Oke, 2012). The measurements start in the area around the Sport complex building (SPENS) and BIG Fashion shopping mall, which has a combination of LCZ 5 (Open midrise) and LCZ 8 (Large low-rise). Then the trajectory goes across the Science Technology Park and University Campus which represent LCZ 5 (Open midrise) and finally goes toward the 'Studentski' park and Danube riverbank as LCZ B (Scattered trees) and LCZ F (Bare soil or sand)/LCZ G (Water) areas (Fig. 2).

2.2. Data collection

The data has been collected using two Mobile Micrometeorological Carts (MMCs) on 29 locations during a hot, summer day of 30th of June 2022 (Fig. 2). Based on the official weather station of Novi Sad, in Rimski Sancevi village, located in the agricultural area, two km outside of the Novi Sad urban area, the average daily 2-m T_a was 29.8 °C, while the maximum was 36.2 °C. Average 2-m RH amounted to 45%, average 10-m wind speed was 2.2 ms^{-1} and clouds and precipitation were absent (Republic Hydrometeorological Service of Serbia, 2023) indicating ideal conditions to study heat waves in a temperate climate. The measurement day was in the middle of a heatwave spanning from the 27th of June to the 5th of July.

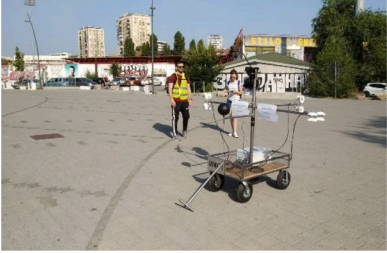
MMCs are small weather stations on wheels, that measure T_a , RH, wind speed, wind direction and solar radiation with Davis sensors, globe temperature with a Testo Globe sensor and short- and longwave radiation in six directions with Hukseflux NR01 sensors (Milosević et al., 2022) (Pictures in Table 1). Accuracy, resolution and range of sensors installed in the MMC, and sources and photos of each sensor component are provided in Supplementary Table S1. Mobile Carts like these are ideal to perform measurements at many different locations in an area. They measure the four important biometeorological variables at a micro scale with high accuracy, making them ideal to predict heat stress. Mobile methods have been found to have a high predictive power for thermal sensations (Deng et al., 2025).

During the measurements, one MMC was stationary in a sun-exposed location next to location 1 on a square. This MMC is the reference station. Another MMC was taken along a trajectory of approximately 2 km with 29 different locations (Fig. 2; Table 1). Those locations varied in SVF, presence of trees and buildings and in ground cover. The diversity of locations was intentional as the authors wanted to cover the diversity of urban micro locations during the measurement campaign. Shading also differed over the day, as the solar angle was changing. Measurements were taken automatically every two minutes. The MMC was stopped at each defined location to perform the measurements. The measurements while the MMC was moving, were not considered in the



Fig. 2. Micrometeorological measurement locations and their classified fisheye lens images of the sky at each location in Novi Sad, Serbia.

Table 1
Description of 29 measurements locations in Novi Sad, Serbia, with their shading type, surface cover, SVF value, description of the micro-environment and photos (Note: photos are just for illustrative purposes, and not all taken at the exact measuring moment, people were always at least 5 m away from the sensors during the measurement).

Location	Shading	Surface	SVF	Microenvironment	Photo
1	open	impermeable	0.74	on a paved square	
2	tree	grass	0.24	in tree shade	
3	open	impermeable	0.79	on a paved square	
4	building	impermeable	0.08	under an overhang	
5	open	impermeable	0.8	on a paved square	
6	mixed	grass	0.27	in tree shade	

(continued on next page)

Table 1 (continued)

Location	Shading	Surface	SVF	Microenvironment	Photo
7	tree	grass	0.67	on an open, grass field	
8	mixed	grass	0.43	in tree shade	
9	open	impermeable	0.69	on a walkway near road junction	
10	building	impermeable	0.01	on a passageway going through a building	
11	mixed	impermeable	0.49	on a paved walkway	
12	tree	grass	0.13	in tree shade	

(continued on next page)

Table 1 (continued)

Location	Shading	Surface	SVF	Microenvironment	Photo
13	mixed	grass	0.53	on a grass field	
14	mixed	impermeable	0.38	on a paved walkway	
15	mixed	permeable tiles	0.1	under a covered bike shelter	
16	mixed	impermeable	0.48	on a small, paved square	
17	mixed	grass	0.39	on a grass field	
18	tree	grass	0.13	in tree shade	

(continued on next page)

Table 1 (continued)

Location	Shading	Surface	SVF	Microenvironment	Photo
19	mixed	impermeable	0.49	on a small, paved square	
20	building	impermeable	0.04	under an overhang	
21	tree	impermeable	0.1	in shade of several trees	
22	tree	impermeable	0.3	on a small, paved square near fountain	
23	building	impermeable	0.05	under an overhang	
24	mixed	grass	0.29	in shade of a young tree	

(continued on next page)

Table 1 (continued)

Location	Shading	Surface	SVF	Microenvironment	Photo
25	mixed	grass	0.57	on grass, near shrubs and parking	
26	tree	grass	0.54	in shade of several trees	
27	open	grass	0.77	on a grass field	
28	open	impermeable	0.82	on the quay walkway	
29	open	sand	0.75	on a sandy beach near the Danube River	

analysis. The trajectory took 80 min to complete including stops and was walked from location 1 to 29 in the morning and afternoon and from location 29 to 1 around noon and during the evening. The trajectory has been repeated during four different times of the day: from 8:00 until 9:20 CEST (morning), from 11:00 until 12:20 CEST (noon), from 15:00 until 16:20 CEST (afternoon) and from 19:30 until 20:50 CEST (evening) to cover different times of the day during summer.

In order to calculate the SVF, fisheye lens photos were made. All hemispherical photographs were taken with the camera positioned 1 m above ground level, using a LEICA SL2 camera equipped with a Canon EF 8–15 mm f/4 L fisheye lens. The camera was oriented vertically upward to capture the full hemispherical view. For reference, the lower edge of the circular frame was aligned with the horizontal plane, and the orientation of the images was recorded relative to cardinal directions. The images were initially captured in RAW (DNG) format and subsequently converted using Capture One 23 with identical processing settings for all images. No binarization or threshold-based conversion to black–white canopy masks was applied; the images were used in their processed color form. Regarding canopy transmissivity, the photographs were taken during the leaf-on period, and thus represent the effective canopy condition at the time of measurement. Consequently, differences between sites reflect the actual canopy structure and obstruction of the sky hemisphere during the measurement period rather than seasonal leaf-off conditions.

2.3. Preprocessing and MRT and PET calculation

The observations had to be pre-processed before analysis. As previously mentioned, only data points at times when the MMC was standing still at one of the locations were used in the analysis, the other data-points have been discarded. A temporal correction has been performed on the trajectory data. A second order polynomial was fitted through the variables measured by the reference MMC. This was done separately for the four parts of the day. For these 80-minute periods a second order polynomial can accurately represent the temporal trend. The measurements from the MMC measuring the locations were then temporally corrected to the conditions at the start of each transect. For the T_a and RH this was done by calculating how much the value of the polynomial at the current time-step deviates from the start of the transect. This value was subtracted from the measurement of the MMC measuring the transect. For the wind speed and radiation fluxes the fractional change in the reference conditions according to the polynomial were calculated and this fractional change was used to correct the trajectory measurements. The procedure for the variables is different because of their different nature. T_a in °C has a non-absolute zero, the measurements are not close to zero and the standard deviation is small compared to the mean. However, wind speed and radiation fluxes can be close to or even zero and have a high variance. Detrending them using an absolute difference would lead to unreliable results, especially for shaded locations, and to sub-zero values.

The fisheye lens photos were converted to SVFs using the Rayman model (Matzarakis et al., 2000). Furthermore, the MRT has been estimated with the formulas below (VDI, 1994 as cited in Thorsson et al., 2007),

$$S_{str} = \alpha_k \sum_{i=1}^6 K_i F_i + \varepsilon_p \sum_{i=1}^6 L_i F_i \quad (1)$$

$$MRT = \sqrt[4]{(S_{str} / (\varepsilon_p \sigma))} - 273.15 \quad (2)$$

Where α_k (0.70) and ε_p (0.97) are the absorption coefficients for short-wave and longwave radiation, σ is the Stefan-Boltzmann constant and S_{str} is the mean radiant flux density. The F_i are the angular factors between a person and an object, for which the standardized values of a standing person have been used (Thorsson et al., 2007). They are 0.22

from the four sides and 0.06 from the top and bottom.

The PET value has been estimated using the PyThermalComfort Python package (Tartarini & Schiavon, 2020). It uses the dry bulb air temperature, MRT, RH and wind speed. The other variables were kept constant at metabolic rate is 1.2, clothing level is 0.5, atmospheric pressure is 1013.25 hPa, position is 2 (standing), age is 23, sex is 1 (male), weight is 75 kg, height is 1.8 m and wme (external work) is 0. These values are chosen to represent a person standing at rest wearing summer clothes. The main interest for this study is in the differences in heat stress between the locations and not between different people, so for the age, gender, weight and height the default values have been taken.

To classify the thermal stress the grade of physiological stress as introduced by Matzarakis and Mayer (1996) has been used. This is presented in Table 2.

2.4. Data analysis

A sensitivity test has been performed to show which micro-meteorological variable was the dominant driver for PET. The sensitivity test was performed by calculating the PET, while increasing one variable from the lowest to the highest value measured at that time of day and keeping the other variables constant on the mean of that time of day. The sensitivity of PET to the range of the meteorological variable can then be seen in the magnitude of the PET difference caused by changing only that variable. Radiant load decomposition has been performed to quantify the contribution of the different directional radiation fluxes. The contributions of each flux to S_{str} were calculated separately showing how much each contributes to the radiant load. . Linear regression was performed to show the effect of the SVF on different radiation fluxes, different radiation fluxes on MRT and the effect of MRT on the PET, as is common practice in heat stress studies (Middel & Krayenhoff, 2019). R-squared was used to show the strength of the regression relationships and p-values were used to show significance. A significance level of 0.05 is used during the whole study. The surfaces were grouped into two categories: grass and impervious. ANCOVA on SVF and the surface covers was performed to show differences between the surfaces and calculate the significance. ANCOVA is a model that combines ANOVA and regression and was chosen because of the dominance of the effect of SVF and the covariance of the two effects. This model prevents confounding of the effect of shading and surfaces.

3. Results

3.1. Meteorological conditions during the measurement day

The 30th of June was a hot day, with a maximum T_a of 36.5 °C measured at location 10 (breezeway), location 11 (walkway) and location 13 (on grass) close to each other on the campus area. Table 3 shows the summary statistics of the key MMC-recorded meteorological variables for the four parts of the day. Incoming solar radiation was strong, since there were no clouds. The MRT was both temporally and spatially

Table 2
PET range for each grade of physiological stress (Matzarakis & Mayer, 1996).

PET	Grade of physiological stress
<4 °C	Extreme cold stress
4–8 °C	Strong cold stress
8–13 °C	Moderate cold stress
13–18 °C	Slight cold stress
18–23 °C	No thermal stress
23–29 °C	Slight heat stress
29–35 °C	Moderate heat stress
35–41 °C	Strong heat stress
>41 °C	Extreme heat stress

Table 3

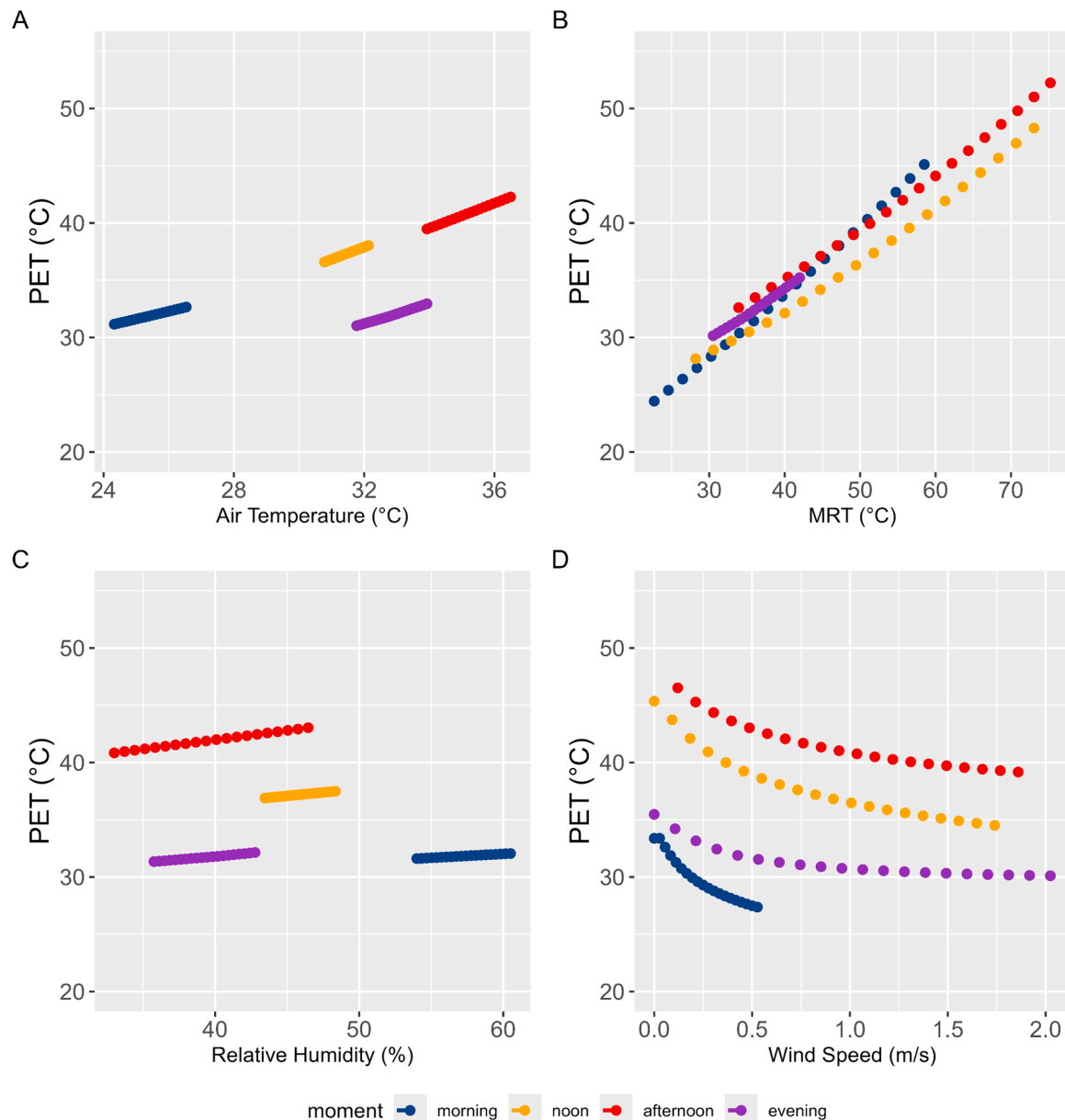
Summary of meteorological conditions during morning, noon, afternoon, and evening periods over all 29 locations on the 30th of June 2022 in Novi Sad, Serbia.

Period	Morning (8:00 CEST)				Noon (11:00 CEST)				Afternoon (15:00 CEST)				Evening (19:30 CEST)			
Parameters	Mean	Min	Max	Sd	Mean	Min	Max	Sd	Mean	Min	Max	Sd	Mean	Min	Max	Sd
Air Temperature (°C)	25.3	24.3	26.5	0.6	31.4	30.8	32.1	0.3	35.6	33.9	36.5	0.7	32.8	31.8	33.9	0.6
MRT (°C)	36.6	22.7	58.5	12.2	51.6	28.2	73.0	15.4	54.2	33.9	75.2	14.9	34.8	30.5	42.0	2.9
Relative Humidity (%)	57.1	54.0	60.5	1.8	46.5	43.5	48.4	0.9	35.8	33.0	46.5	2.7	40.6	35.8	42.8	1.7
Wind Speed (m/s)	0.1	0.0	0.5	0.1	0.8	0.0	1.7	0.5	0.9	0.1	1.9	0.5	0.4	0.0	2.0	0.5
PET (°C)	32.4	24.7	47.1	6.9	38.2	29.3	48.8	6.2	42.3	32.2	56.3	7.2	32.8	30.0	37.0	1.6

variable. The highest measured MRT amounted to 75.2 °C at location 9 in the afternoon. The RH ranged from maximum 61% in the morning to 33% in the afternoon. The RH increased again slightly in the evening. Wind speeds were generally very low ($<1.5 \text{ ms}^{-1}$) and peaked slightly during the middle of the day. The maximum PET of the day was 56.3 °C at 15:38 CEST at location 13 on grass near the dorms. Heat stress classification varied over the locations from slight to extreme during the morning, moderate to extreme during the noon and afternoon and was moderate to strong during the evening.

3.2. Drivers of heat stress

The first goal of this research is to investigate which variables are dominant drivers for heat stress. During most of the day this turned out to be the MRT. The range of the calculated MRT, when keeping the other variables constant at their mean value for that part of the day, causes a 20.7 °C, 20.1 °C and 19.6 °C difference in PET during the morning, noon and afternoon (Fig. 3B). The MRT during the evening had little variation, causing only 5.1 °C difference in PET. PET also showed to be quite

**Fig. 3.** PET sensitivity to T_a (A), MRT (B), RH (C) and wind speed (D) for the different parts of the day.

sensitive to T_a , but T_a varied little spatially compared to MRT causing only a maximum of 2.8 °C difference in the afternoon and even lower during the rest of the day (Fig. 3A). However, the diurnal cycle of T_a caused clear temporal variation in the PET. The wind speed mainly caused differences at very low values ($<1 \text{ ms}^{-1}$) but can still lower the PET up to 10.9 °C around noon (Fig. 3D). The PET was the least sensitive to RH, causing a maximum 2.2 °C difference during the afternoon (Fig. 3C). The R^2 s of the MRT and PET of the measurement locations show that MRT is indeed a dominant driver for PET for most of the day (Fig. 4). The PET of the measurement locations did not show to be significantly related to the T_a , RH or wind speed. For wind speed log-log linear regression was performed, since wind and PET have a power relation.

3.3. Effect of directional radiation components

The following analysis focuses on the contribution of directional radiation components to the total radiant load on the human body and assesses their variability across different surroundings. The total S_{str} of each site is divided into the share that each flux contributes to it, which shows how important each directional flux is to the total contribution of radiation to heat stress. The measurement locations are grouped based on the characteristics of their surroundings: (A) open location over grass, (B) open locations over paved surface, (C) open location over sand, (D) shaded locations by buildings over paved surface, (E) shaded locations by trees over grass, (F) shaded locations by trees over pavement, (G) locations with mixed shade over grass, and (H) locations with mixed shade over pavement. The radiant load decomposition of each location separately can be found as Supplementary Figure S2.

Across all surroundings and times of day, lateral radiation is the dominant directional radiation component (Fig. 5), consistent with the large lateral surface area of the human body. Within the lateral fluxes, longwave radiation consistently contributes more to total absorbed radiation than solar radiation, yet it is spatially far less variable: its contribution shifts only modestly between surroundings, whereas solar radiation exhibits strong contrasts depending on shading type. The most striking contrast is between open and building-shaded locations: under building overhangs or tunnels ($\text{SVF} \approx 0.04$), solar radiation contributes

virtually nothing to radiant load at any time of day, while open locations ($\text{SVF} \approx 0.75\text{--}0.77$) show large solar contributions during daytime hours. Tree-shaded and mixed-shaded locations occupy an intermediate position, but the averaged values in Fig. 5 mask important within-group variability: individual locations can oscillate between near-full sun exposure and deep shade depending on the exact solar angle relative to the canopy or building geometry, as is clearly visible in Supplementary Figure S2. Shading also suppresses longwave radiation: building-shaded locations show the sharpest reduction in downwelling and lateral longwave fluxes, while tree- and mixed-shaded locations display a more moderate but still clearly visible reduction compared to open sites. This suggests that obstacles not only block direct solar radiation but also reduce re-emitted thermal radiation from surrounding heated surfaces. In the evening, solar contributions diminish across all locations and longwave radiation becomes the primary driver of remaining differences in radiant load. Notably, open paved locations (B) retain a markedly higher evening radiant load than the other open sites (A, C), which points to a heat-storage effect of paved surfaces that continues to radiate after sunset. Differences attributable to surface cover (grass vs. paved) are otherwise subtle throughout the day and difficult to interpret from Fig. 5 alone, as they are confounded by co-varying shading conditions and the limited number of sampled locations per group.

3.4. Effect of sky view factor on radiation

In this section, the effect that different urban structures and trees have on the different radiative components and PET is examined quantitatively. The SVF is used to quantify the amount of structures in the surrounding of the measurement location. The T_a , RH and wind speed were also analysed this way but did not show any correlation with SVF. The MRT is positively correlated to the SVF with the strongest fit for the noon (Fig. 6A). A 10% reduction in SVF led to a lowering of the MRT for the morning, noon, afternoon and evening of 3.2 °C, 5.2 °C, 4.7 °C and 0.5 °C, respectively. The PET shows a similar response to SVF as the MRT, but with lower R-squared and slope (Fig. 6B). A 10% reduction in SVF led to decrease of the PET for the morning, noon and afternoon of 1.7 °C, 1.8 °C and 2.0 °C, respectively. During the evening, the PET is not significantly related to the SVF.

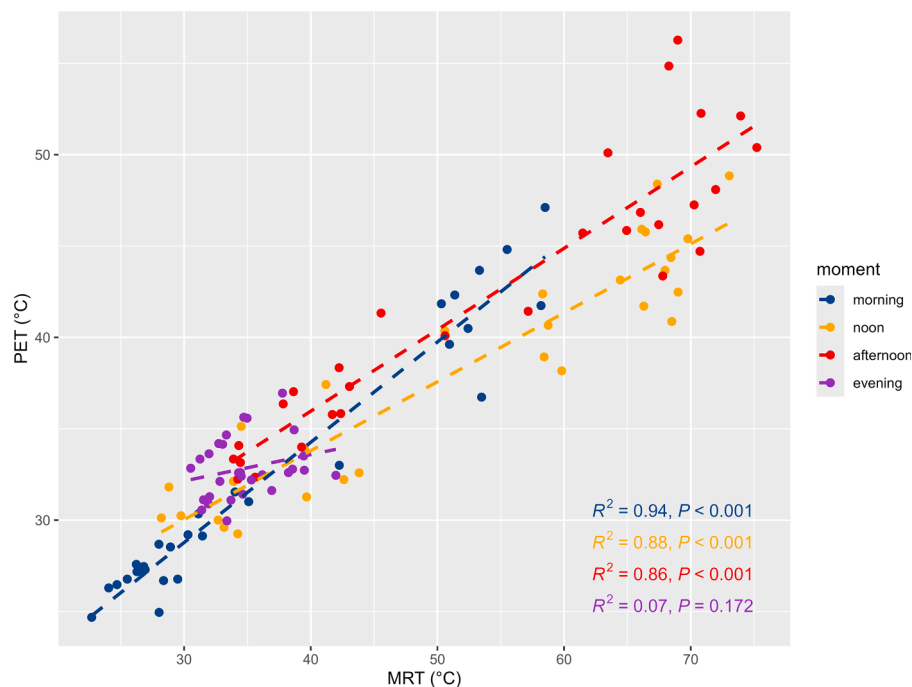


Fig. 4. Relationship between observed MRT and PET (A) for the different parts of the day.

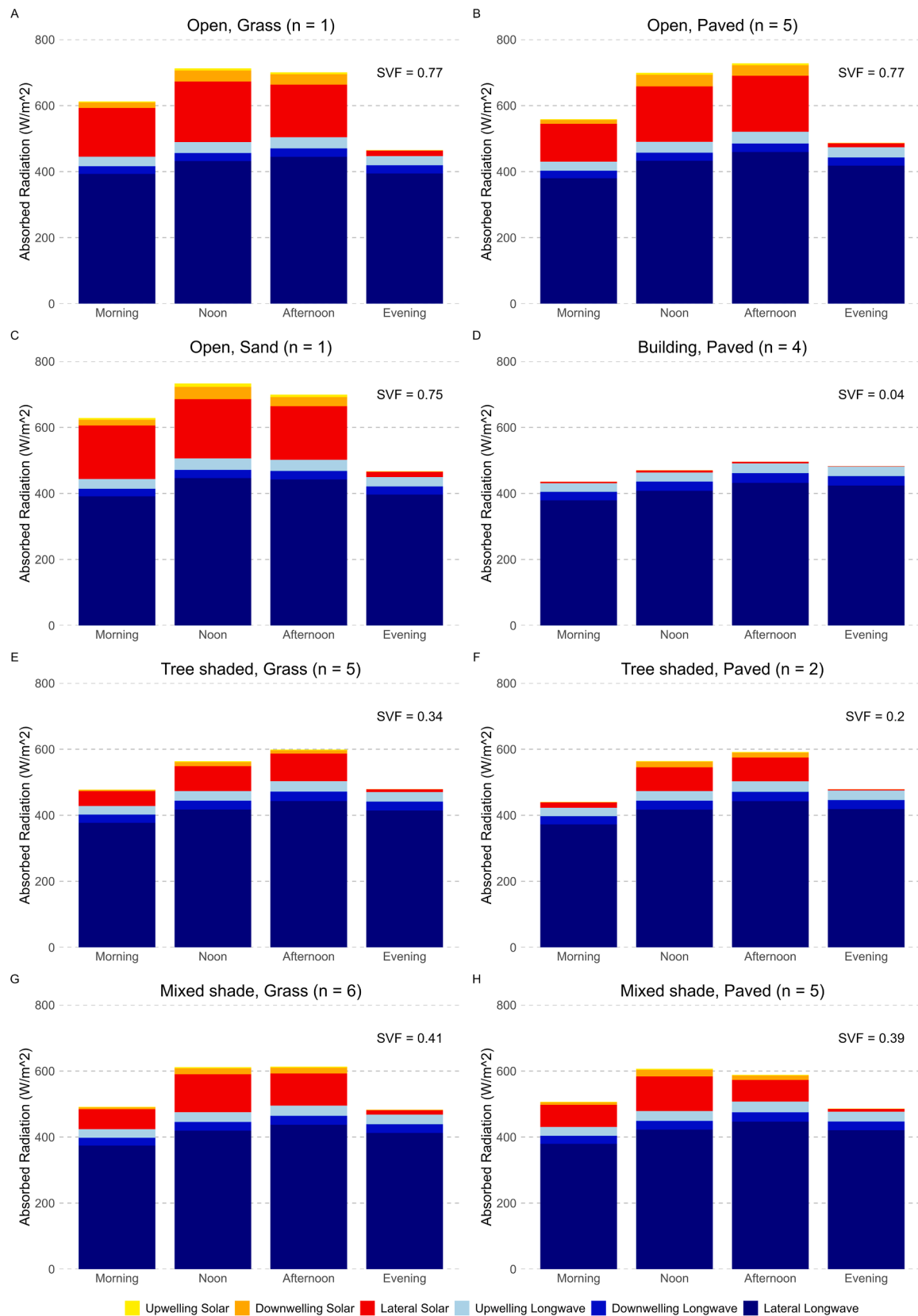


Fig. 5. Directional decomposed radiant load over the measurement day (30th June 2022) in Novi Sad, Serbia. Locations are grouped by surrounding: A) open location over grass, B) open locations over paved surface, C) open location over sand, D) shaded locations by buildings over paved surface, E) shaded locations by trees over grass, F) shaded locations by trees over pavement, and G) locations with mixed shade over grass, and H) locations with mixed shade over pavement.

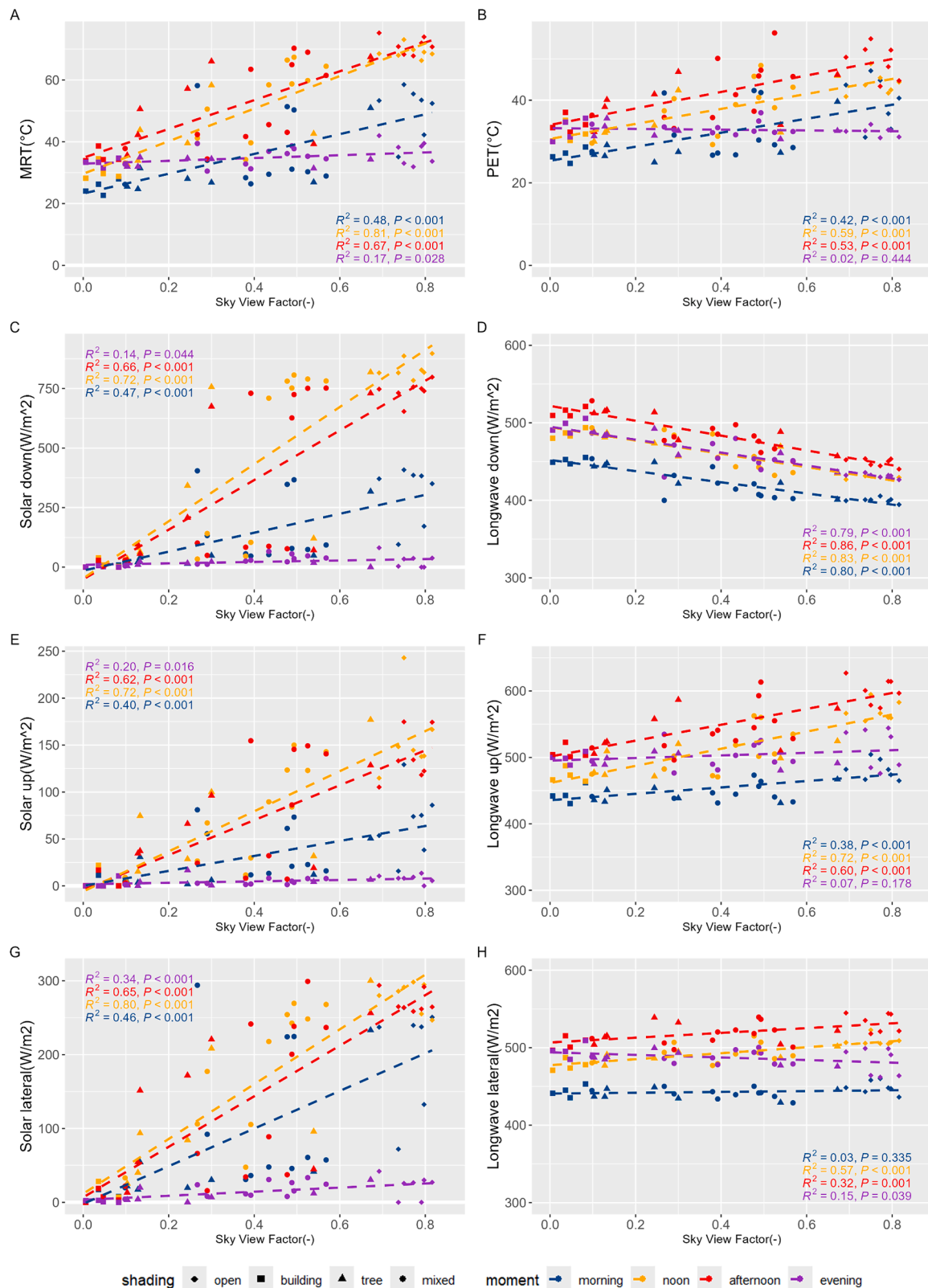


Fig. 6. MRT (A), PET (B) and radiation components (C–H) compared to reference plotted against SVF. NOTE: Different colours indicate different parts of the day, while different shapes indicate different shading obstacles.

The directional radiation fluxes also show clear patterns when plotted against SVF. At lower SVFs, all solar radiation fluxes decreased towards 0 for all periods of the day (Fig. 6C, E and G). The downwelling and lateral solar radiation show clustering. There is one group with

medium to high SVFs and minimal reduction in radiation and a group with low to medium SVFs and a big reduction in radiation. The long-wave radiation shows different patterns for the different directional components. A decrease in SVF causes an increase in downwelling

longwave radiation (Fig. 6D), but a decrease in the other components (Fig. 6F and H). The fit for the downwelling longwave radiation is best out of all radiation components ($R^2 > 0.79$). The lateral longwave radiation shows the poorest fits, with even no fit at all in the morning. For lateral longwave radiation, the trend is reversed in the evening compared to the other times of day. Longwave radiation shows smaller responses to SVF than the solar radiation as can be seen by the magnitude of response in Fig. 6C-E (30 - 100 W/m² for longwave and 200 - 900 W/m² for solar radiation).

Fig. 6 also shows whether a location is mainly open or has trees, buildings or a combination nearby, as is represented by the shapes of the datapoints. Open locations have the highest SVF, and these locations are similar to the reference for all fluxes. Locations shaded by built obstacles, such as tunnels and overhangs, have the lowest SVF. These are amongst the coolest, having a decrease compared to the hottest open locations of up to 45 °C for MRT and 24 °C for PET. Tree and mixed shade locations have sizeable spread in their SVF. The building, tree and mixed shaded locations do not show differences in their average reduction of MRT and PET at the same SVF, but the spread around the trendline is largest for tree and mixed shaded areas with a SVF between 0.2 and 0.6.

3.5. Effect of surfaces on radiation

The surfaces in urban areas are also expected to have an influence on the radiation balance. In this study, only the surface cover below the MMC was noted and not the surface cover at the sides. The results of statistical testing using ANCOVA between grass and impermeable surfaces can be seen in Table 4, the model also included SVF to avoid confounding. Shading type was not included in the model, since there was no difference in shading strength between the different shading types at the same SVF (Section 3.4). For albedo, only measurements with downwards solar radiation larger than 50 W/m² for the morning and 100 W/m² for the noon and afternoon were used to make sure the albedo could be correctly estimated. Albedo was not analysed in the evening, since incoming solar radiation is very low for all locations at that time. The upwards longwave radiation, which is emitted by the surface, was lower over grass than impervious surfaces, which was significant for the afternoon and evening. The fraction of solar radiation that is reflected (albedo) was higher for grass surfaces, but not significantly. For the total radiation to a human body (MRT), there was also no significant difference between grass and impermeable surfaces (lowest p-value (evening) = 0.085).

Table 4

Difference in radiation components between grass and impermeable locations with p-value. Positive differences mean that impermeable locations have higher values than grass locations. NOTE: Bold text indicates statistically significant p-values.

Moment	Difference between grass and impermeable	P-value (ANCOVA)
Longwave Radiation Up (W/m2)		
Morning	-6.99	0.263
Noon	-15.46	0.063
Afternoon	-28.59	0.004
Evening	-18.75	0.013
Solar reflectance(albedo) (-)		
Morning	0.03	0.247
Noon	0.06	0.206
Afternoon	0.06	0.122
MRT (°C)		
Morning	-1.25	0.733
Noon	-0.98	0.734
Afternoon	-1.5	0.683
Evening	-1.85	0.085

4. Discussion

In this research, heat stress was analysed using detailed micro-meteorological measurements during a hot summer day in Novi Sad, Serbia. PET was used to quantify the heat stress. First, the sensitivity of PET to different meteorological variables will be discussed (4.1). Then the focus will be on the importance of the different radiation components (4.2) and their response to the surrounding (4.3 & 4.4). The discussion will end with a reflection on the limitations of the methodology (4.5).

4.1. Drivers of heat stress

Although PET was sensitive to both MRT and T_a, spatial variability in heat stress was primarily explained by MRT due to its larger variation between locations. This confirms our hypothesis and is in accordance to results in similar studies which all find MRT as the most important spatial variable (Aleksandrowicz & Pearlmutter, 2023; Ali-Toudert & Mayer, 2007; Holst & Mayer, 2011; Kántor et al., 2016, 2018; Lai et al., 2018; Lee et al., 2013; Middel & Kravynhoff, 2019; Sangman et al., 2025). Differences exist between climates; in the hot desert climate (BWh) of Phoenix, Arizona, for example, differences were overall larger, causing larger differences in PET. Additionally, wind speed and PET had a positive relationship in their study (Middel & Kravynhoff, 2019). These differences are consistent with the difference in climate, since wind speed is known to be able to increase heat stress in extremely hot and arid climates (Foster et al., 2022). Previous literature have often found T_a as important to PET, with only a slightly lower importance than MRT. For example, Lee et al. (2014) found that MRT ($R^2=0.69$) explained PET slightly better than T_a ($R^2=0.64$), which was a large deviation from results from their previous work in 2013 ($R^2=0.89$ for MRT and $R^2=0.59$ for T_a) (Lee et al., 2013). They proposed that this small difference is because they averaged variables over six hours in the 2014 study and over 1 hour in the 2013 study, stressing the importance of timescale of the measurements. This highlights the importance of considering the diurnal cycle when interpreting PET sensitivities. Since this work uses instantaneous PET values, the extremely high sensitivity to MRT could be expected. PET also exhibited sensitivity to wind speed, but the relationships between PET and wind speed for the trajectory data were not significant. However, we must note that research with MMCs is less suitable for analysing the effect of surrounding on wind speeds, since longer time-series or models are needed to characterize the fluctuating nature of wind speed.

4.2. Effect of directional radiation components

Radiation decomposition revealed that lateral radiation fluxes dominated radiant load. This can be explained by the fact that human bodies, on average, have 88% of their area on the sides (Thorsson et al., 2007). Although longwave radiation contributed most to absolute radiant load, spatial variability was primarily driven by solar fluxes. These results are comparable to the results by Middel and Kravynhoff (2019) and confirm that also in a temperate heatwave lateral solar radiation is responsible for most variation in radiant load and thus MRT. Locations with few obstacles nearby had a lot of incoming solar radiation. Those locations also experienced higher longwave radiation fluxes. This suggests that lack of shading also causes nearby surfaces to heat up more and thus emit more longwave radiation, adding to the heat stress. Longwave radiation changes persisted for individual locations even after shading conditions changed and into the evening after sunset. This is in agreement with the results by Lee et al. (2014), who found that downward solar radiation already explained 90% of variation in MRT and Fang et al. (2023) who found that downward solar radiation explained 95% of variation in MRT for unshaded locations and 67% for shaded locations. These results show that, despite lateral longwave radiation being the largest contributor to radiant load, decreasing incoming solar

radiation is a very effective way to reduce heat stress because of its covariance with the other radiation fluxes.

4.3. Effect of sky view factor on radiation

The observed relationships between SVF and the radiation fluxes were consistent with theoretical expectations, and most have strong correlations, especially during the noon and afternoon at which time all R^2 s except for lateral longwave radiation are above 0.5. All significant correlations were positive during the day except for the downwelling longwave radiation. This pattern is expected because a high SVF means less shading so increased incoming and reflected solar radiation and consequently leads to more heating up of surrounding surfaces and thus emission of longwave radiation. However, downwelling longwave radiation increases when there are obstacles above the MMC, since trees and urban structures have a higher longwave radiation emission than the clear atmosphere. Solar radiation turned out to be clustered, with mostly very high or very low values of downwards and lateral solar radiation. This is expected, since blocking of direct sunlight is important to reduce these fluxes. Low SVF locations were generally shaded, whereas intermediate SVF locations showed greater variability depending on solar geometry. Built structures provided more consistent shading than vegetation, although both achieved comparable cooling effects at similar SVF values. Other studies have also found similar cooling effects at the same SVF between trees and buildings (Colter et al., 2019; Middel et al., 2016). This indicates that trees and urban structures are both effective options for thermal stress reduction. In the evening, the forementioned system worked differently, since there was almost no solar radiation. However, downwards and lateral longwave radiation were increased during those times at places with a lot of obstacles (= low SVF). This effect has also been observed in previous works (Coutts et al., 2016; Middel & Krayenhoff, 2019). Although obstacles indeed slightly increased evening MRT through longwave radiation trapping, this did not produce a significant relationship between SVF and PET. This effect is an important consideration in heat stress reduction, but did not negate the strong heat stress reduction during daytime.

4.4. Effect of surface on radiation

Consistent with earlier findings, the effect of the surface on the different radiation components was limited compared to the effect of shading. Grass was shown to emit significantly less longwave radiation than impervious surfaces during the afternoon and evening. Solar reflectance was higher over grass and MRT was lower during all periods, but this was not significant. Emission of longwave radiation during the noon and MRT during the evening approached statistical significance ($0.05 < p\text{-value} < 0.1$). While surfaces are commonly found as much less influential than shading, our finding are less strong than of related literature. The maximum (non-significant) MRT reduction of 2 °C over grass, is notably <5 °C as found by Lindberg et al. (2016) or 3 °C to >10 °C – depending on conditions – as found by Middel and Krayenhoff (2019). However, the effect of surfaces is complex and differs at different temperatures (Fang et al., 2024). Surfaces that are more reflective, have reduced longwave radiation emission, but increased solar reflection (Middel et al., 2020). Our findings reflect this pattern, although it is only significant during the afternoon. This means that the total effect on MRT is a trade-off of these effects. Soil and plant moisture status also plays a large role, with the difference between grass and concrete becoming smaller and even reversing during dry periods (Hoffmann et al., 2025). During the measurement campaign, most of the grass cover in Novi Sad was dry and yellow, which influences its radiative properties. The results of the surface analysis do align well with the earlier discussed strong correlation between solar radiation and MRT, suggesting that most variation, especially early in the day, could already be explained by solar irradiation. Future research should additionally investigate lateral surfaces, since lateral radiation fluxes turned out to be

very dominant.

4.5. Limitations

These data have given various insights in heat stress and especially the role that different radiation fluxes play, but the methods also have limitations. Mobile micrometeorological measurements are sensitive to issues with sensor response time (Parlow & Foken, 2021). This may introduce temporal lag effects in measurements taken with an MMC. This was already considered by stopping for each location, but research shows that longer stops make the measurements more accurate (Qi et al., 2021). However, longer stops make it hard to compare multiple locations within the same conditions, since measurements will take much longer. The whole trajectory took around 80 min using the current method, which already must be corrected for by the temporal de-trending using a reference MMC, but there is a limit to how much of the effects of different conditions and solar altitude this can remove. Therefore, taking a longer time will make the impact of this larger. Samples measured on a trajectory also inherently have spatial correlation. The combination of spatial and temporal dependence of the samples means the independence assumption is not completely met and some temporal variation and solar-geometry effects might still be present even in the corrected data. This is especially the case for the morning and evening in which the conditions are changing faster. This could result in overstating of statistical significance. Additional sources of measurement uncertainty that could be researched are the distance between radiation sensors and obstacles and tilting of the device. A limitation of the methodology is that lateral surface cover was not recorded, so while lateral radiation did show great importance to heat stress, the contribution of lateral surface cover to the differences in radiation could not be quantified. The mobile method is not suitable to gain insight into wind speed as discussed before. To get a complete view of the urban climate it is therefore important to use multiple types of measurements and models. It is also important to consider the broader urban and meteorological context, such as the urban heat island effect, nearby water bodies and the atmospheric dynamics within the city.

5. Conclusion

In this research mobile meteorological carts were used to measure T_a , RH, six-directional radiation and wind speed at diverse urban locations in Novi Sad, Serbia, which has a temperate oceanic climate. All locations were visited four times during a cloud-free summer day. The meteorological variables were used to uncover the patterns in urban heat stress and to answer the question which meteorological variable was the dominant cause of spatial differences in heat stress in summer under clear-sky, low-wind conditions. The most important meteorological variable for spatial differences in PET showed to be the MRT causing a decrease in PET of up to 20.7 °C (morning). T_a and RH caused mainly temporal differences in heat stress, with those of RH being small. Wind also caused moderate differences in PET at low wind speeds, but this effects levels of at higher wind speeds. The mean radiant flux density was decomposed into the different directional radiation components, to see which has the largest contribution to heat stress. Lateral radiation has the largest directional contribution to radiant load. Solar radiation fluxes have smaller, but more variable, contributions to radiant load than longwave radiation fluxes. Blocking of direct incoming solar radiation is the most important factor in the surrounding and already predicts most of the differences in absorbed radiation during daytime conditions. Locations under built structures have the lowest SVFs and are consistently among the coolest. Trees can reach the same cooling capacity but provide more variable shading. Surfaces were less important for radiation than was expected from literature. Emitted longwave radiation was significantly lower over grass than over impervious materials during the second half of the day. Reflected shortwave radiation was higher and MRT was lower over grass, but this could not be proven

significant. Overall, directional radiant load decomposition provides process-based insight into which radiative pathways and urban features most strongly shaped heat stress under the studied conditions, and can therefore support more evidence-based, context-specific heat-mitigation assessment. However, this study does not consider lateral surfaces, nor does it take into account variability in surface conditions within a class. More thorough research into surface effects, with less strong variability in other variables, could uncover stronger links between surfaces and heat stress.

CRedit authorship contribution statement

Maaïke van der Veld: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis. **Gert-Jan Steeneveld:** Writing – review & editing, Supervision, Investigation. **Stevan Savić:** Writing – review & editing, Resources, Funding acquisition, Data curation. **Jelena Dunjić:** Writing – review & editing, Resources, Investigation. **Daniela Arsenović:** Writing – review & editing, Resources, Data curation. **Dragan Milošević:** Writing – review & editing, Supervision, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization.

Declaration of competing interest

The authors declare no competing interest.

Acknowledgements

DM and GJS acknowledge support from the 4TU-program HERITAGE (HEat Robustness In relation To AGEing cities), funded by the High Tech for a Sustainable Future (HTSF) program of 4TU, the federation of the four technical universities in the Netherlands. SS, JD and DA gratefully acknowledge the financial support of the Ministry of Science, Technological Development and Innovation of the Republic of Serbia (Grants No. 451-03-137/2025-03/200125 & 451-03-136/2025-03/200125). Also, this research is partly supported by the Interreg-IPA CBC Croatia-Serbia program through the project INTERCLIM (ID: HR-RS00094). Finally, the authors gratefully acknowledge all colleagues and students who assisted with the field measurements and data collection, whose dedication and support were essential for the successful execution of this study.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at [doi:10.1016/j.scs.2026.107717](https://doi.org/10.1016/j.scs.2026.107717).

Data availability

Data will be made available on request.

References

- Aleksandrowicz, O., & Pearlmuter, D. (2023). The significance of shade provision in reducing street-level summer heat stress in a hot Mediterranean climate. *Landscape and Urban Planning*, 229, Article 104588. <https://doi.org/10.1016/j.landurbplan.2022.104588>
- Ali-Toudert, F., & Mayer, H. (2007). Thermal comfort in an east-west oriented street canyon in Freiburg (Germany) under hot summer conditions. *Theoretical and Applied Climatology*, 87(1), 223–237. <https://doi.org/10.1007/s00704-005-0194-4>
- Arsenović, D., Lužanin, Z., Milošević, D., Dunjić, J., Nikitović, V., & Savić, S. (2023). The effects of summer ambient temperature on total mortality in Serbia. *International Journal of Biometeorology*, 67(10), 1581–1589. <https://doi.org/10.1007/s00484-023-02520-5>
- Aviv, D., Guo, H., Middel, A., & Meggers, F. (2021). Evaluating radiant heat in an outdoor urban environment: Resolving spatial and temporal variations with two sensing platforms and data-driven simulation. *Urban Climate*, 35, Article 100745. <https://doi.org/10.1016/j.uclim.2020.100745>
- Chapman, S., Watson, J. E. M., Salazar, A., Thatcher, M., & McAlpine, C. A. (2017). The impact of urbanization and climate change on urban temperatures: A systematic review. *Landscape Ecology*, 32(10), 1921–1935. <https://doi.org/10.1007/s10980-017-0561-4>
- Colter, K. R., Middel, A. C., & Martin, C. A. (2019). Effects of natural and artificial shade on human thermal comfort in residential neighborhood parks of Phoenix, Arizona, USA. *Urban Forestry & Urban Greening*, 44, Article 126429. <https://doi.org/10.1016/j.ufug.2019.126429>
- Coutts, A. M., White, E. C., Tapper, N. J., Beringer, J., & Livesley, S. J. (2016). Temperature and human thermal comfort effects of street trees across three contrasting street canyon environments. *Theoretical and Applied Climatology*, 124(1), 55–68. <https://doi.org/10.1007/s00704-015-1409-y>
- Deng, P., Li, Z., Wang, X., Tang, Z., & Hong, B. (2025). Comparing fixed and mobile measurement techniques for evaluating outdoor thermal comfort. *Sustainable Cities and Society*, 124, Article 106330. <https://doi.org/10.1016/j.scs.2025.106330>
- Du, J., Liu, L., Chen, X., & Liu, J. (2020). Field assessment of neighboring building and tree shading effects on the 3D radiant environment and Human thermal comfort in summer within urban settlements in Northeast China. *Advances in Meteorology*, 2020(1), 1–19. <https://doi.org/10.1155/2020/8843676>
- Dunjić, J., Milošević, D., Kojić, M., Savić, S., Lužanin, Z., Šećerov, I., & Arsenović, D. (2021). Air humidity characteristics in “local climate zones” of Novi Sad (Serbia) based on long-term data. *ISPRS International Journal of Geo-Information*, 10(12), 810. <https://doi.org/10.3390/ijgi10120810>
- Fang, Z., Zhang, F., Guo, Z., Zheng, Z., & Feng, X. (2024). Investigation into the outdoor thermal comfort on different urban underlying surfaces. *Urban Climate*, 55, Article 101911. <https://doi.org/10.1016/j.uclim.2024.101911>
- Fang, Z., He, H., Mao, Y., Feng, X., Zheng, Z., & Guo, Z. (2023). Investigating an accurate method for measuring the outdoor mean radiation temperature. *International Journal of Thermal Sciences*, 188, Article 108219. <https://doi.org/10.1016/j.ijthermalsci.2023.108219>
- Foster, J., Smallcombe, J. W., Hodder, S., Jay, O., Flouris, A. D., & Havenith, G. (2022). Quantifying the impact of heat on human physical work capacity; part II: The observed interaction of air velocity with temperature, humidity, sweat rate, and clothing is not captured by most heat stress indices. *International Journal of Biometeorology*, 66, 507–520.
- He, B.-J., Ding, L., & Prasad, D. (2020). Relationships among local-scale urban morphology, urban ventilation, urban heat island and outdoor thermal comfort under sea breeze influence. *Sustainable Cities and Society*, 60, Article 102289. <https://doi.org/10.1016/j.scs.2020.102289>
- He, C., Kim, H., Hashizume, M., Lee, W., Honda, Y., Kim, S. E., Kinney, P. L., Schneider, A., Zhang, Y., Zhu, Y., Zhou, L., Chen, R., & Kan, H. (2022). The effects of night-time warming on mortality burden under future climate change scenarios: A modelling study. *The Lancet Planetary Health*, 6(8), e648–e657. [https://doi.org/10.1016/S2542-5196\(22\)00139-5](https://doi.org/10.1016/S2542-5196(22)00139-5)
- Hoffmann, C., Geissler, A., & Wicki, A. (2025). Differences in microclimate of paved and green areas. *Urban Climate*, 64, Article 102595. <https://doi.org/10.1016/j.uclim.2025.102595>
- Holst, J., & Mayer, H. (2011). Impacts of street design parameters on human-biometeorological variables. *Meteorologische Zeitschrift*, 20, 541–552. <https://doi.org/10.1127/0941-2948/2011/0254>
- Hondula, D. M., Balling, R. C., Andrade, R., Scott Krayenhoff, E., Middel, A., Urban, A., Georgescu, M., & Sailor, D. J. (2017). Biometeorology for cities. *International Journal of Biometeorology*, 61(1), 59–69. <https://doi.org/10.1007/s00484-017-1412-3>
- Höppe, P. (1999). The physiological equivalent temperature – a universal index for the biometeorological assessment of the thermal environment. *International Journal of Biometeorology*, 43(2), 71–75. <https://doi.org/10.1007/s004840050118>
- ISO. (1998). *ISO 7726: Ergonomics of the thermal environment—Instruments for measuring physical quantities*.
- Kántor, N., Chen, L., & Gál, C. V. (2018). Human-biometeorological significance of shading in urban public spaces—Summertime measurements in Pécs, Hungary. *Landscape and Urban Planning*, 170, 241–255. <https://doi.org/10.1016/j.landurbplan.2017.09.030>
- Kántor, N., Kovács, A., & Takács, Á. (2016). Small-scale human-biometeorological impacts of shading by a large tree. *Open Geosciences*, 8(1), 231–245. <https://doi.org/10.1515/geo-2016-0021>
- Klemm, W., Heusinkveld, B. G., Lenzholzer, S., & van Hove, B. (2015). Street greenery and its physical and psychological impact on thermal comfort. *Landscape and Urban Planning*, 138, 87–98. <https://doi.org/10.1016/j.landurbplan.2015.02.009>
- Kottek, M., Grieser, J., Beck, C., Rudolf, B., & Rubel, F. (2006). World Map of the Köppen-Geiger climate classification updated. *Meteorologische Zeitschrift*, 15(3), 259–263. <https://doi.org/10.1127/0941-2948/2006/0130>
- Kousis, I., Pigliatelli, I., & Pisello, A. L. (2021). Intra-urban microclimate investigation in urban heat island through a novel mobile monitoring system. *Scientific Reports*, 11(1), 9732. <https://doi.org/10.1038/s41598-021-88344-y>
- Lai, A., Kwok, Y. T., Maing, M., & Ng, E. (2018). Regression modelling of radiant fluxes on different view factors under shading in a densely built environment. *Architectural Science Review*, 61(1–2), 15–28. <https://doi.org/10.1080/00038628.2017.1409614>
- Lamberti, G., Vista, D. D., Leccese, F., & Salvadori, G. (2025). A novel methodology for evaluating urban surface overheating and its impact on pedestrians' Radiative heat exposure using infrared thermography. *Building and Environment*, 278, Article 112981. <https://doi.org/10.1016/j.buildenv.2025.112981>
- Lamberti, G., Della Vista, D., Leccese, F., & Salvadori, G. (2026). On the geometrical limitations of the globe thermometer for assessing pedestrian radiative exposure in outdoor settings. *Energy and Buildings*, 350, Article 116609. <https://doi.org/10.1016/j.enbuild.2025.116609>
- Lee, H., Holst, J., & Mayer, H. (2013). Modification of Human-biometeorologically significant radiant flux densities by shading as local method to mitigate heat stress in

- summer within urban street canyons. *Advances in Meteorology*, 2013(1), 1–13. <https://doi.org/10.1155/2013/312572>
- Lee, H., Mayer, H., & Schindler, D. (2014). Importance of 3-D radiant flux densities for outdoor human thermal comfort on clear-sky summer days in Freiburg, Southwest Germany. *Meteorologische Zeitschrift*, 23, 315–330. <https://doi.org/10.1127/0941-2948/2014/0536>
- Li, Z., Feng, X., & Fang, Z. (2022). A modified method to measure outdoor mean radiant temperature: Comparison between two-hemisphere method and six-direction integral method. *Building and Environment*, 221, Article 109292. <https://doi.org/10.1016/j.buildenv.2022.109292>
- Liu, K., You, W., Chen, X., & Liu, W. (2022). Study on the influence of globe thermometer method on the accuracy of calculating outdoor mean radiant temperature and thermal comfort. *Atmosphere*, 13(5), 809. <https://doi.org/10.3390/atmos13050809>
- Lindberg, F., Onomura, S., & Grimmond, C. S. B. (2016). Influence of ground surface characteristics on the mean radiant temperature in urban areas. *International Journal of Biometeorology*, 60(9), 1439–1452. <https://doi.org/10.1007/s00484-016-1135-x>
- Matzarakis, A. (2000). Estimation and calculation of the mean radiant temperature within urban structures. *Biometeorology and urban climatology at the turn of the millenium* (Ed. by R.J.de Dear, J.D.Kalma, T.R.Oke and A. Auliciems): Selected papers from the Conference ICB-ICUC '99, Sydney, WCASP-50, WMO/TD No. 1026, 273–278.
- Matzarakis, A., & Mayer, H. (1996). Another kind of environmental stress: Thermal stress. *WHO Collaborating Centre for Air Quality Management and Air Pollution Control*, 18, 7–10.
- Matzarakis, A., Mayer, H., & Iziomon, M. G. (1999). Applications of a universal thermal index: Physiological equivalent temperature. *International Journal of Biometeorology*, 43(2), 76–84. <https://doi.org/10.1007/s004840050119>
- Middel, A., & Krayenhoff, E. S. (2019). Micrometeorological determinants of pedestrian thermal exposure during record-breaking heat in Tempe, Arizona: Introducing the MaRTy observational platform. *Science of The Total Environment*, 687, 137–151. <https://doi.org/10.1016/j.scitotenv.2019.06.085>
- Middel, A., Selover, N., Hagen, B., & Chhetri, N. (2016). Impact of shade on outdoor thermal comfort—a seasonal field study in Tempe, Arizona. *International Journal of Biometeorology*, 60(12), 1849–1861. <https://doi.org/10.1007/s00484-016-1172-5>
- Middel, A., Turner, V. K., Schneider, F. A., Zhang, Y., & Stiller, M. (2020). Solar reflective pavements—a policy panacea to heat mitigation? *Environmental Research Letters*, 15 (6), Article 064016. <https://doi.org/10.1088/1748-9326/ab87d4>
- Milošević, D., Dunjić, J., Stojšavljević, R., Žgela, M., Savić, S., & Arsenović, D. (2023). Analysis of long- and short-term biometeorological conditions in the Republic of Serbia. *International Journal of Biometeorology*, 67(6), 1105–1123. <https://doi.org/10.1007/s00484-023-02482-8>. 2023 67:6.
- Milošević, D., Savić, S., Sećerov, I., & Dunjić, J. (2022). Introducing mobile micrometeorological carts (MMCs) for urban and non-urban micrometeorological measurements. <https://doi.org/10.5194/ems2022-59>.
- Nazarian, N., Krayenhoff, E. S., Bechtel, B., Hondula, D. M., Paolini, R., Vanos, J., Cheung, T., Chow, W. T. L., de Dear, R., Jay, O., Lee, J. K. W., Martilli, A., Middel, A., Norford, L. K., Sadeghi, M., Schiavon, S., & Santamouris, M. (2022). Integrated assessment of urban overheating impacts on Human life. *Earth's Future*, 10(8), Article e2022EF002682. <https://doi.org/10.1029/2022EF002682>
- Oke, T. R., Mills, G., Christen, A., & Voogt, J. A. (2017). *Urban climates*. Cambridge University Press.
- Parlow, E., & Foken, T. (2021). *Ground-based mobile measurement systems. Chapter 50* (pp. 1351–1367). Springer Handbook of Atmospheric Measurements. https://doi.org/10.1007/978-3-030-52171-4_50
- Qi, Q., Meng, Q., Wang, J., & Ren, P. (2021). Developing an optimized method for the 'stop-and-go' strategy in mobile measurements for characterizing outdoor thermal environments. *Sustainable Cities and Society*, 69, Article 102837. <https://doi.org/10.1016/j.scs.2021.102837>
- Republic Hydrometeorological Service of Serbia. (2023). *Meteorological yearbook 1 climatological data 2022*.
- Sangman, J., & Sookuk, P. (2025). The shading effect of single trees on human thermal sensation during summer: A case study in Jeju, Republic of Korea. *International Journal of Biometeorology*, 69, 1003–1014. <https://doi.org/10.1007/s00484-025-02873-z>
- Santamouris, M. (2020). Recent progress on urban overheating and heat island research. Integrated assessment of the energy, environmental, vulnerability and health impact. Synergies with the global climate change. *Energy and Buildings*, 207, Article 109482. <https://doi.org/10.1016/j.enbuild.2019.109482>
- Savić, S., Arsenović, D., Lužanin, Z., Milošević, D., Dunjić, J., Sećerov, I., Kojić, M., Radić, I., Harhaji, S., & Arsić, M. (2023). Hospital admission tendencies caused by day-to-day temperature changes during summer: A case study for the city of Novi Sad (Serbia). *International Journal of Biometeorology* 2023, 67(4), 695–704. <https://doi.org/10.1007/s00484-023-02447-x>
- Steenneveld, G.-J., Heusinkveld, B., Holtslag, B., Hove, B., & Jacobs, C. (2014). Spatial variability of the Rotterdam urban heat island as influenced by urban land use: Rotterdam urban heat island. *Journal of Geophysical Research*, 119, 677–692. <https://doi.org/10.1002/2012JD019399>
- Stewart, I. D., & Oke, T. R. (2012). Local climate zones for urban temperature studies. *Bulletin of the American Meteorological Society*, 93(12), 1879–1900. <https://doi.org/10.1175/BAMS-d-11-00019.1>
- Tartarini, F., & Schiavon, F. (2020). Pythermalcomfort: A python package for thermal comfort research. *SoftwareX*, 12, Article 100578. <https://doi.org/10.1016/j.softx.2020.100578>
- Thorsson, S., Lindberg, F., Eliasson, I., & Holmer, B. (2007). Different methods for estimating the mean radiant temperature in an outdoor urban setting. *International Journal of Climatology*, 27(14), 1983–1993. <https://doi.org/10.1002/joc.1537>
- United Nations Department of Economic and Social Affairs. (2019). *Urban and rural population growth and world urbanization prospects*.
- VDI. 1994. Environmental meteorology, interactions between atmosphere and surface; calculation of short- and long wave radiation. Part I: Climate, VDI 3789, Part 2: VDI/ DIN- Handbuch Reinhaltung der Luft, Band 1b, Düsseldorf.
- Wang, A., Dai, Y., Zhang, M., & Chen, E. (2025). Exploring the cooling intensity of green cover on urban heat island: A case study of nine main urban districts in Chongqing. *Sustainable Cities and Society*, 124, Article 106299. <https://doi.org/10.1016/j.scs.2025.106299>
- Wujeska-Klaue, A., & Pfautsch, S. (2020). The best urban trees for daytime cooling leave nights slightly warmer. *Forests*, 11(9), 945. <https://doi.org/10.3390/f11090945>