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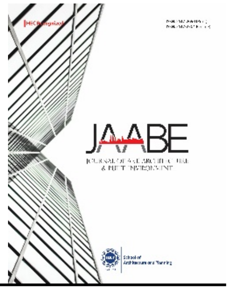

Title: **How T_{mrt} affects PET assessment in outdoor environments: A comparative study**

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How T_{mrt} Affects PET Assessment in Outdoor Environments: A Comparative Study

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Abstract

Many studies have explored outdoor thermal comfort during the last several years, ever since it has been strongly related to human health and well-being. The physiological equivalent temperature (PET) is one of the most commonly used thermal comfort indexes. It has been approved and applied within different urban spaces and climates. This study is a comparative research that explored the importance of using mean radiant temperature (T_{mrt}) in PET assessment by employing two different methods. The first method was used to calculate PET based on three measured variables including relative humidity, wind velocity, and air temperature. RayMan software was utilized to perform the calculations. The second method was used to calculate PET by combining Envi-met and RayMan. Envi-met allowed four sets of calibrated data, including the data of air temperature (T_a), wind velocity (W_v), relative humidity (RH), and mean radiant temperature (T_{mrt}). RayMan software used the calibrated results to calculate PET. These methods were explored in outdoor environments at Annaba, Algeria, characterized by a Mediterranean climate. The results showed significant differences in PET values, especially through the warmest times of the day. The first method highlighted very high PET values, where $40 \leq PET < 51$ at noon. At the same time, using T_{mrt} gave precise PET values ($30 \leq PET \leq 32$). Based on these findings, we can confirm the importance of considering T_{mrt} in PET calculation, which allows one to identify the accurate comfort range.

***Keywords*:** Algeria, Mean Radiant Temperature (T_{mrt}), mediterranean climate, Physiological Equivalent Temperature (PET), thermal comfort

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Introduction

Thermal comfort is a well known health related issue which has been discussed and investigated, frequently. Many researchers have focused only on indoor thermal comfort (Bughio et al., 2020; Mahar, 2021; Mahar et al., 2019; Mahar & Attia, 2018; Semahi et al., 2020). On the other hand, several studies have also explored outdoor thermal comfort, since it significantly correlates with human health and well-being. A comfortable urban environment may enhance human activities. Outdoor thermal comfort is important, especially in regions with extreme temperatures and climatic conditions (Matallah et al., 2021). Indeed, climatic conditions and human factors are known to affect it (Andreou, 2013). Liu et al. (2016) proved the importance of microclimatic variables for human outdoor thermal comfort. Many indices have been developed to gauge the latter, for instance, physiologically equivalent temperature (PET) Höppe (1999), perceived temperature (PT) (Jendritzky et al., 2000; Potchter et al., 2018; Staiger et al., 2012), universal thermal climate index (UTCI) (Fiala et al., 2012; Jendritzky et al., 2012), and the predicted mean vote (PMV) (Berkovic et al., 2012; de Freitas & Grigorieva, 2015; Lai et al., 2014; Potchter et al., 2018).

These indices were established based on the mechanism of heat conductivity between human body and outdoor climate (Liu et al., 2016). Several studies explored PET within different urban spaces and environments. Furthermore, PET was correlated with the user's thermal perception.

For thermal comfort assessment, thermo-physiological parameters were combined with meteorological variables (Mayer, 1993; VDI, 2008). Numerical simulation models were used in several studies focusing on climatic variables influential at the street level. These studies were based on the application of software to optimise the accuracy of the thermal comfort index (Acero & Herranz-Pascual, 2015; Klemm et al., 2015; Lee et al., 2016; Morakinyo et al., 2017). RayMan and ENVI-met are two standard softwares mainly used for the calculation of outdoor thermal comfort. Relative humidity, mean radiant temperature (T_{mrt}), surface temperature, air temperature, and wind velocity can be calculated using ENVI-met simulation software (Acero & Herranz-Pascual, 2015). Outdoor thermal comfort can be calculated also using four of the above microclimatic variables. Furthermore, clothing insulation and metabolic rate are also considered (Watanabe et al., 2014).

This study aimed to analyze the T_{mrt} effect in PET assessment. To this end, comparative research at the street was carried out in a Mediterranean clismate.

Methods and Materials

The method presented in this study is concerned with the comparison of PET at three streets. Every segment has a measurement point. The first approach involved calculated PET based on three climatic variables (relative humidity, air temperature, and wind velocity), according to the weather file records of 2017. In comparison, the second approach included four climatic variables (wind velocity, relative humidity, air temperature, and T_{mrt}), using in situ measurement and calibration process. The choice of streets depended on the criteria mentioned in Table 1, that is, building height, street orientation, street morphology, vegetative species, and distribution.

The above two approaches were explored and applied in Annaba city, Algeria. The city has a Mediterranean climate with Hot Summer (Csa), according to the classification of climate by (Köppen, 2020). Figure 1 illustrates the conceptual framework of this study.

Table 1

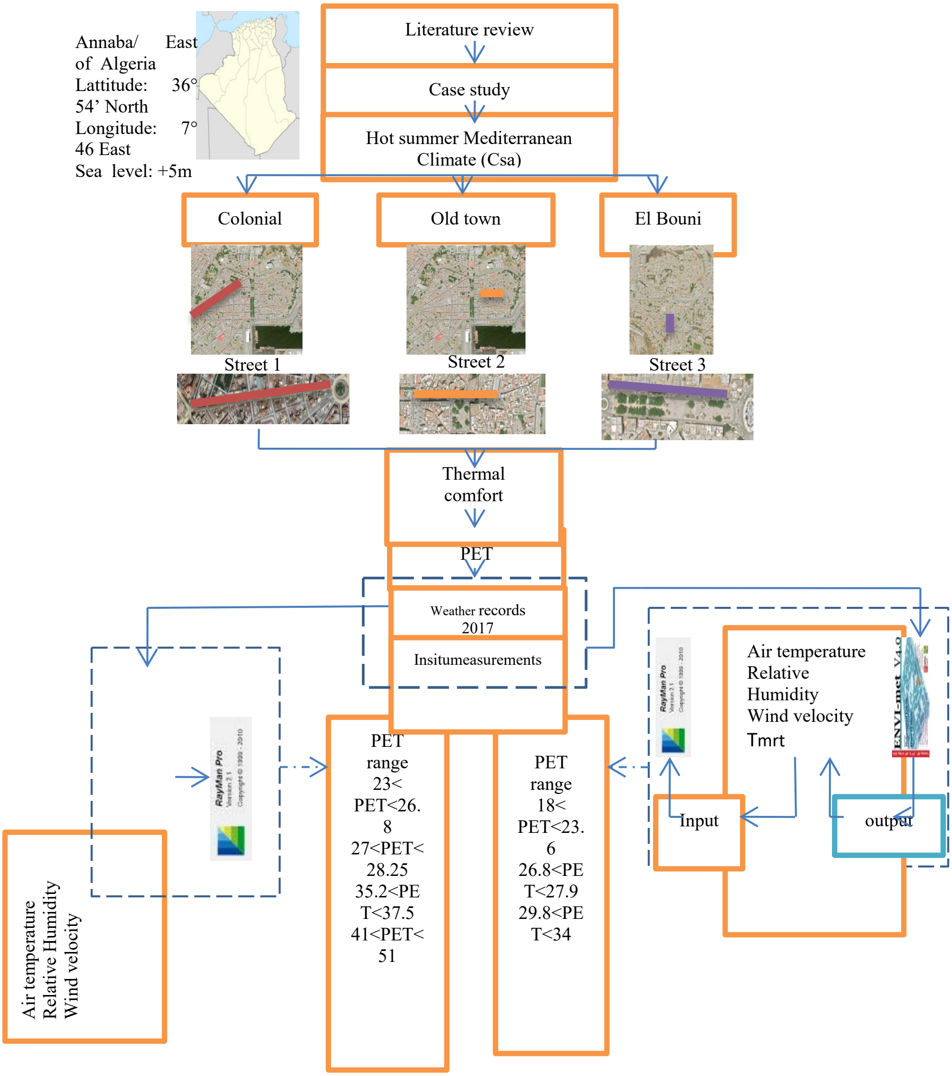
The Three Selected Streets and their Characteristics

Characteristics of Streets	Selected Streets		
	1	2	3
Length	1682.7ft	1060.4 ft	983.2ft
Orientation	NE/SW	E/W	N/S
Building height	52.4ft	36–42.6 ft	39.3 - 50.8ft
Vegetative elements (Trees)	0	3	0

E/W: East/West, NE/SW: NorthEast/South West, N/S: North/South

Figure 1

Conceptual Framework of the Study



Calculating PET

PET values were calculated using RayMan software, which is considered as one of the most reliable tools for modelling radiations and bioclimatic models used for the prediction of thermal comfort (Cohen et al., 2013; Elnabawi et al., 2016). RayMan has been endorsed for its use in several climatic regions and urban spaces (Cohen et al., 2013; Gulyás et al., 2006; Hwang et al., 2011; Lin et al., 2013; Matzarakis et al., 2007). PET is calculated using multiple factors, for instance, relative humidity, mean radiant temperature (T_{mrt}), wind velocity, and air temperature. Calculations were made for three representative summer days in 2017, that is, 28th of July, 8th of August and 26th of August.

PET values based on air temperature, wind velocity, air humidity, mean radiant temperature (T_{mrt}), human activity, and clothing were calculated using RayMan. The time of the day and the specific period of the year can also be adjusted keeping in view other variables, for example, location, altitude, the albedo of the surrounding surfaces, the related air turbidity, and the Bowen ratio of the ground surface (Elnabawi et al., 2016; Hwang et al., 2011; Matzarakis et al., 2007).

Computing PET using Three Climatic Variables (T_a, RH, and Wv)

This approach calculates PET based on three climatic variables, that is, relative humidity (RH), air temperature (Ta), and wind velocity (Wv). We applied the same climatic variables at the three selected streets (Fig. 1), based on the weather file records of 2017. Moreover, every street had a specific PET calculating point.

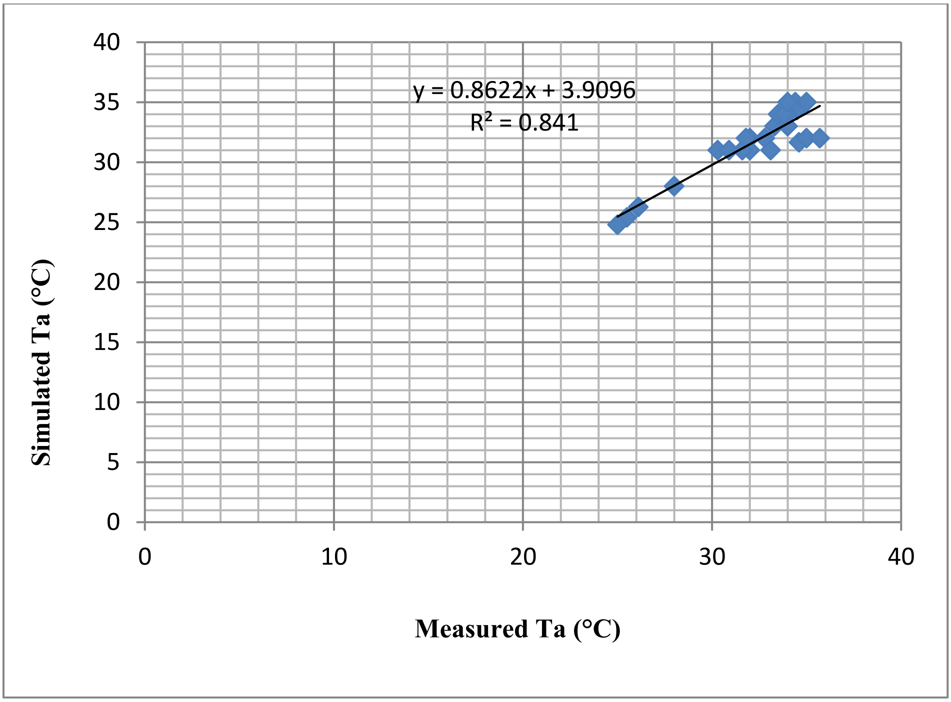
Computing PET using Four Calibrated Microclimatic Variables (T_a, RH, Wv, and T_{mrt})

This approach involved in situ measurements undertaken in summer 2017 within the Csa climate of Annaba, Algeria. A measurement point was determined for every street using Lm 8000 tool (thermometer and illuminometer, hygrometer and thermo-anemometer), placed at the height of 1.1m above the ground. Continuous monitoring of air temperature, relative humidity, and wind velocity was performed from 8 am to 8 pm on the selected days, that is, 28th of July, 8th of August, and 26th of August.

The temporal microclimate model and spatial height performance model were applied in this study using ENVI-met 4 software. A building's architectural and natural vegetation models can be generated using ENVI-met simulation (Wu & Chen, 2017). The simulation model was first calibrated and validated keeping in view the measured and simulated air temperature. Figure 2 depicts the correlation between the measured and simulated air temperature (Elnabawi et al., 2013; Taleghani & Berardi, 2018). The same method was also used in previous studies to validate the calibration of the simulated model (Bughio et al., 2021; Ibrahim et al., 2021; Mahar et al., 2019). The value of 0.841 shows a solid correlation and proves the simulated model as calibrated and validated. Subsequently, the calibrated data of the selected four microclimatic variables, that is, relative humidity, T_{mrt}, wind velocity, and air temperature was obtained from the simulation model. Hence, PET was calculated from 8 am to 8 pm based on the calibrated data (Klemm et al., 2015; Lobaccaro & Acero, 2015; Morakinyo et al., 2017; Taleghani & Berardi, 2018).

Figure 2

Correlation between the Simulated and Measured Air Temperature



Results

The application of the two PET computing approaches allowed the analysis of the T_{mrt} effect on PET. Indeed, the first approach highlighted using weather records data (08/08/2017), where the same climatic data have been administered in the three streets of Annaba, Algeria. In comparison, the second approach included using in situ measurements and Envi-met, which allowed the calculation of the calibrated values of microclimatic variables used in this study, including air temperature, relative humidity, T_{mrt}, and wind velocity (See Table 1).

Microclimatic Variables (Calibration Results)

A substantial variation in air temperature was noticed in all streets selected for this study. The recorded temperature at 8 am was 25.2°C in Street 1, 24.9°C in Street 2 (Medina), and 26°C in Street 3. It shows that the lowest recorded outdoor temperature at 8 am was in Street 2. High temperatures were noticed during different hours (12 pm, 2 pm, and 4 pm). However, at 10 am, similar temperatures were recorded in Street 1 and Street 2 (30.5°C - 30.6°C). Lower temperature values were observed in Street 2, where the temperature varied between 31.1°C - 31.5°C at noon, 33.2°C - 33.5°C at 2 pm, and 34.3°C - 34.5°C at 4 pm. On the other hand, the recorded temperature varied between 31.6°C - 32°C at noon, 33.9°C - 34.2°C at 2 pm, and 34.6°C - 34.9°C at 4 pm in Street 1. The highest recorded temperature at noon was 34.7°C in Street 3.

In streets 1 and 2, relative humidity showed a greater variation throughout the recorded time, that is, from 8 am to 8 pm. At 8 pm, the recorded relative humidity in Street 1 varied between 81-83%. It was below 83% in Street 2, while the lowest recorded humidity was 57% in Street 3, as shown in Table 2.

Noticeable differences were recorded in the mean radiant temperature (T_{mrt}). The lowest recorded values occurred at 8 am in Street 1 (13.3°C - 13.5°C), Street 2 (13.6°C - 13.8°C) and Street 3 (12.8°C), respectively. Nevertheless, lower T_{mrt} values were recorded in Street 1 (18.7-19°C) at noon, as compared to Street 2 (19.1-19.3°C) and Street 3 (21.6°C). Lastly, the recorded values of wind velocity remained at a low level in all selected streets (Table 2).

PET Results

Calculated using weather records data and RayMan software

The results highlighted small differences in PET values at the selected streets in the first approach. Indeed, the lowest PET values (23.6°C, 23.2°C, and 23.4°C) were recorded at 8 pm. In comparison, the highest PET values were recorded at noon (50.7°C and 51°C). Moreover, some other hours, such as 10 am and 2 pm, were characterized by high PET values (Table 2).

Calculated using Four Calibrated Microclimatic Variables (T_a, RH, Wv, and T_{mrt})

The findings highlighted differences among the three streets. In streets 1 and 2, PET values were nearly equal to each other, mainly through the hottest period of the day. For instance, PET value was 26.5°C at noon in Street 1, whereas it was 26.4°C at the same time in Street 2. However, a decrease in temperature was noted at 8 pm (23.1°C) in Street 2, in contrast to a temperature of 23.6°C noted in Street 1. On the other hand, PET values during the day remained higher in Street 3, than in streets 1 and 2 (Table 2). However, an exception occurred at 8 am when PET value 19.9°C was recorded in Street 3, whereas it was 20.1°C in Street 1 and 20°C in Street 2. According to the results, street orientation of PET values and H/W (height to canyon width) ratio have a positive correlation. During the hottest period of the day, relative values of PET were noted in streets 1 and 2, despite the orientation difference between them(NE/SW Street 1, E/W Street 2). Alternatively, H/W ratio was lower (1.89) in Street 2 than Street 1 (around 2), which shows a decent shade level in Street 2. H/W equivalent to 0.29 was noted in Street 3, which had a north-south orientation. It showed a lower and adequate shade level in Street 3.

Comparative Analyses of Two-Set Data with Two Calculating Approaches

The results highlighted a noticeable difference in PET values. The incorporation of the T_{mrt} variable in PET assessment allowed the reducing of PET values. Indeed, the highest differences among the three streets were recorded at noon, ±24°C in streets 1 and 2. In comparison, the difference in Street 3 was equivalent to ±22.6°C. At 8 pm, PET values were almost the same on all the three streets (Fig. 3). Indeed, the difference between the two-set data was equivalent to 0 and 0.1, in Street 1 and Street 2, respectively. In comparison, Street 3 recorded the highest distinction (±1.4), as mentioned in Table 3.

Table 2

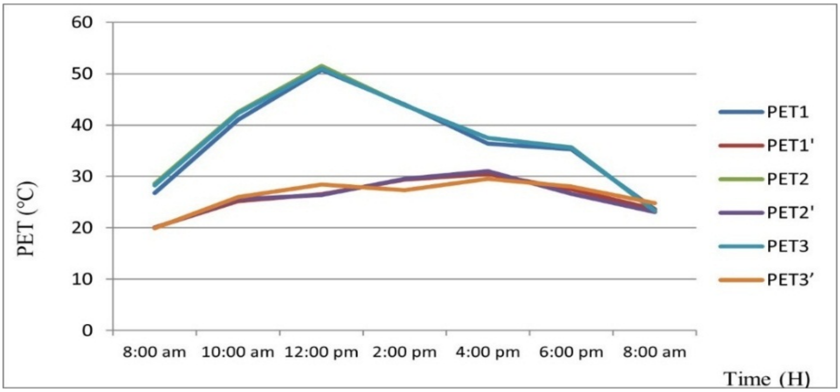
Weather Records and Microclimatic Data of Three Representative Days in CSA

	Street 1							Street 2							Street 3						
	08/08/2017			26 &28, August 2017				08/08/2017			26 &28, August 2017				08/08/2017			26 &28, August 2017			
Time	T(a) (°C)	RH (%)	Wv (m/s)	T(a) (°C)	RH (%)	Wv (m/s)	T_{mrt} (°C)	T(a) (°C)	RH (%)	Wv (m/s)	T(a) (°C)	RH (%)	Wv (m/s)	T_{mrt} (°C)	T(a) (°C)	RH (%)	Wv (m/s)	T(a) (°C)	RH (%)	Wv (m/s	T_{mrt} (°C)
8 am	28	62	5.4	25.2-25.3	below 94	0.2-0.4	13.3-13.5	28	62	5.4	24.9-25.1	96	0.3-0.4	13.6-13.8	28	62	5.4	26	48	0	12.8
10 am	36.7	29	11.2	30.5-30.6	68	0.5-0.9	17.7-17.9	36.7	29	11.2	30.5-30.6	below 73	0.9-1.2	18.3-18.5	36,7	29	11.2	33.4	32	0	19.9
12 pm	42	19	13	31.6-32	57-59	0.9-1.9	18.7-19	42	19	13	31.1-31.5	58-61	2-2.6	19.1-19.3	42	19	13	34.7	28.5	0.2	21.6
2 pm	38	23	22.3	33.9-34.2	71	0.8-1.5	21.2-21.5	38	23	22.3	33.2-33.5	70-74	1.6-1.9	21.7-22	38	23	22.3	31.6	50	2.4	20.5
4 pm	34.8	40	25.9	34.6-34.9	31-32	1-2.	23.9-24.3	34.8	40	25.9	34.3-34.5	below 33	2.4-2.9	24.5-24.8	34,8	40	25.9	33.2	25	2.6	23.8
6 pm	35	28	24.1	31-31.2	65	1-1.97	22.6-22.8	35	28	24.1	30.9-31.1	65-69	2.1-2.5	22.5-22.8	35	28	24.1	31.6	44	0.5	23.6
8 am	29	55	16.6	27.5-27.6	81-83	0.7-1.4	19	29	55	16.6	27.3-27.4	below 83	1-1.3	below 19.07	29	55	16.6	28.8	57	0.5	20.1

T_{mrt}: Mean radiant temperature; T(a): Air temperature; Wv: Wind velocity; RH: Relative humidity

Figure 3

PET Variance by Applying the Two Methods



PET1, PET2, PET3: Calculated PET without considering T_{mrt}.

PET1', PET2', PET3': Calculated PET considering T_{mrt}.

Table 3

Comparison of PET Values based on the Two Methods

Time	Street 1		Street 2		Street 3	
	PET1 (°C)	PET1'(°C)	PET2(°C)	PET2'(°C)	PET3 (°C)	PET3'(°C)
8 am	26.8	20.1	27	20	28.25	19.9
10 am	41	25.2	41.5	25.6	42.4	26
12 pm	50.7	26.5	51	26.4	51	28.4
2 pm	44	29.4	43.9	29.5	44	27.3
4 pm	36.4	30.5	37.5	31	37.5	29.5
6 pm	35.3	27.5	35.2	26.6	35.6	28
8 am	23.6	23.6	23.2	23.1	23.4	24.8

PET1,PET2, PET3: Calculated PET without considering T_{mrt}.

PET1',PET2', PET3': Calculated PET considering T_{mrt}.

At 8 am, PET results reflected a neutral thermal sensation vote in Street 1. However, the differences were more noticeable in Street 2 and Street 3. Indeed, PET calculations based on the first approach reflected slightly warm thermal sensation vote. In contrast, using T_{mrt} in PET calculations highlighted a neutral thermal sensation vote (See tables 3 and 4).

The most noticeable differences were recorded at 10 am, noon, and 2 pm on the three selected streets, where PET 1, PET 2, and PET 3 reflected extremely hot temperatures, while PET 1', PET 2', and PET 3' emphasized a slightly warm thermal sensation vote. At 6 pm, PET 1, PET 2, and PET 3 defined a hot temperature, while PET 1', PET 2', and PET 3' highlighted a slightly warm thermal sensation vote. However, at 8 am, PET values within the two methods defined a neutral thermal sensation vote (See Table 3).

Discussion

Human thermal comfort simulations for outdoor comfort can be performed using ENVI-met modelling. It is possible to estimate the current and future climatic conditions using local climate data in the modelling software. In this study, the monitoring of climatic variables was performed in the selected streets of Annaba, Algeria. The simulation model was created in ENVI-met, which was then calibrated and validated using air temperature data (Acero & Herranz-Pascual, 2015a; Chen & Ng, 2013; Müller et al., 2014). PET was calculated using RayMan software, based on the calibrated data which provides more accurate thermal comfort models. The results showed agreement between T_a and T_{mrt} values among the measured and simulated data (Lee et al., 2016; Tan et al., 2016). To optimizethe accuracy of the thermal comfort index, a numerical simulation model at the street level was used in many studies based on climatic variables (Acero & Herranz-Pascual, 2015; Klemm et al., 2015; Lee et al., 2016; Morakinyo et al., 2017).

The findings of this study showed the relevance of considering T_{mrt} in PET assessment. As mentioned in Table 2, the variation in PET values between the two sets of data reached ±22.6°C. Air temperature, relative humidity, and wind speed T_{mrt} remained the principal variables in PET assessment. These findings are strongly supported by previous works in which thermal comfort index and street walkability were combined in the Mediterranean area. They proved that considering T_{mrt} in PET assessment is essential and it allows for more accuracy in PET results. Moreover, excluding the T_{mrt} parameter causes the overestimation of PET values. Previous studies highlighted the consequences of considering imprecise radiation fluxes which can generate an overestimation of T_{mrt} and systematically of PET (Ali-Toudert & Mayer, 2006; Chen et al., 2014; Ketterer & Matzarakis, 2014; Zölch et al., 2016).

This study proved the efficacy of T_{mrt} in PET calculation and its impact on thermal sensation vote. Indeed, the results showed significant differences in thermal perception during three specific hours of the day. In case of ignoring T_{mrt}, thermal perception was inclined towards 'extremely hot', which is not typical for this climate (Cohen et al., 2013; Labdaoui et al., 2021; Potchter et al., 2018).

The current study concentrated on representative heat days with ultimate weather conditions in Annaba, Algeria, characterized by a Mediterranean climate. By introducing a forcing option for computing the daily cycle of relative humidity and air temperature using ENVI-met software, we can enhance these variables' day evolutions and allow a good correlation of the calculated T_{mrt} and measurement data (Lee et al., 2016; Lobaccaro & Acero, 2015).

Conclusion

This comparative study was carried out at the street level with different morphologies in the Mediterranean climate of Annaba, Algeria. It proved the necessity of considering T_{mrt} in PET assessment. Excluding this variable generates an overestimation of PET. This study also highlighted the accuracy of the calibrated data, a complementary outcome of previous investigations regarding outdoor thermal comfort.

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