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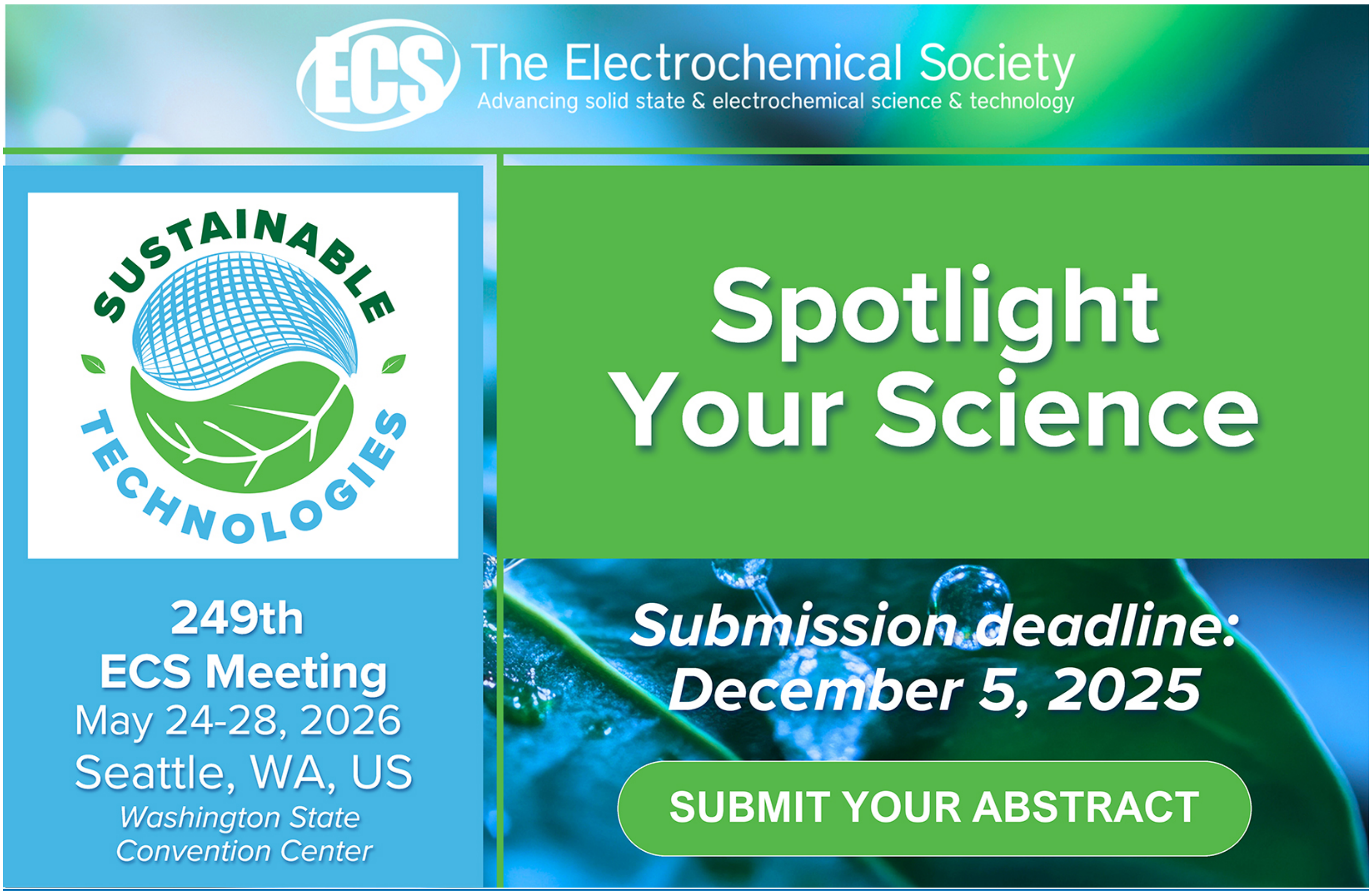

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Impact of Urban Vegetation on Thermal Comfort Indices in the city of Burgos, Spain

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Abstract. Outdoor thermal comfort is essential for the usability of urban open spaces, influencing how people experience and interact with outdoor environments. However, its assessment is difficult to quantify due to multiple factors, including urban configuration, the daily and seasonal variation of meteorological conditions, and socio-demographic characteristics. This study evaluates thermal comfort in the city of Burgos, Spain, using six widely recognized thermal comfort indices, analysing their inputs requirements, methodological differences, and variations in results. Environmental and radiative data were collected during summer 2024 at three urban locations, each including a vegetated and a non-vegetated site. Measurements were taken using environmental and radiative sensors, and the indices were calculated with the *pythermalcomfort* library. Results show that indices incorporating radiative components (PET, UTCI, WBGT) indicate higher thermal stress, particularly in unshaded areas exposed to direct solar radiation. Locations such as Pedro Maldonado square and the old heliport exhibited extreme thermal stress during peaks sunlight hours, whereas vegetated areas recorded significantly lower levels of thermal discomfort. These findings highlight the critical role of urban vegetation and shading in mitigating heat stress. The study emphasizes the importance of selecting suitable thermal comfort indices and incorporating green infrastructure into urban planning to enhance outdoor comfort and resilience in the context of climate change.

1. Introduction

Urban outdoor thermal comfort has become a critical factor in city design and planning, particularly in the context of rapid urban expansion and climate change. The way people interact with different urban spaces and the level of comfort they experience significantly impact public health, well-being, and urban livability. To systematically assess thermal comfort in outdoor environments, researchers often rely on thermal comfort indices, which classify levels of thermal stress and discomfort based on climatic conditions and physiological factors [1].

These indices can be derived from direct environmental measurements or through simulations that model thermal conditions in urban areas. However, a key challenge in outdoor environments is the dynamic nature of climatic conditions, which vary both spatially and temporally [2]. Understanding these variations requires detailed knowledge of the built environment, including the presence or absence of vegetation, the types and arrangement of materials, and the use of urban elements, all of which influence microclimatic conditions.

In this study, environmental and radiative measurements were conducted at some locations in the city of Burgos, Spain. For each site, two measurement points with differing urban configurations were selected: one with vegetation and one without. Six widely recognized thermal indices were calculated to provide a comprehensive evaluation of thermal comfort: the Discomfort Index (DI), Humidex, Normal Effective Temperature (NET), Physiologically Equivalent Temperature (PET), Universal Thermal Climate Index (UTCI), and Wet Bulb Globe Temperature (WBGT). By incorporating multiple index comparison, this study offers an assessment of urban thermal behaviour in different situations.

2. Materials and methods

2.1. Study area

Burgos is located in the northeastern part of the Castilla y León region, at an elevation of 865 meters above sea level. The Arlanzón River runs through the city from east to west, dividing it into two parts. The climate in Burgos is temperate, characterized by warm summers and the absence of a well-defined dry season. According to the Köppen-Geiger classification, it falls under the Cfb category [3].

Environmental data collection was conducted at three distinct locations across the city, with measurements taken at two specific points within each site (Figure 1). These points were selected to compare microclimatic variations between areas with tree cover and adjacent open spaces without vegetation.

Figure 1. Measurement locations in the city of Burgos, Spain.

The first set of measurements was carried out on July 19, 2024, between 10:30 and 13:00, at Pedro Maldonado square and Castilla y León Avenue (Location 1). The second set was conducted on August 21, 2024, during two-time intervals: from 10:30 to 13:00 and from 19:00 to 21:00, at the esplanade of the 'Museo de la Evolución Humana' (MEH) and on the banks of the Arlanzón river (Location 2), a few meters from the MEH. The final set of measurements took place on August 27, 2024, with continuous data collection from 10:30 to 20:00 at an old heliport and a nearby grove of trees (Location 3).

2.2. Environmental measurements and instrumentation

All the environmental data was measured every 30 seconds using a Campbell Scientific MetSENS500 environmental sensor and the BlackGlobe-L thermometer. Both devices were mounted on a Manfrotto tripod at a height of 1.4 meters [4]. Additionally, each setup included an Apogee SP110 pyranometer, installed on a horizontal surface to measure solar radiation. Data were continuously logged and averaged every minute using two Campbell Scientific CR1000 dataloggers.

2.3. Thermal comfort indices

Six thermal comfort indices were calculated using the pythemalcomfort package (version 3.0.0) [5]. These indices include the Discomfort Index (DI), Humidex, Normal Effective Temperature (NET), Physiological Equivalent Temperature (PET), Universal Thermal Comfort Index (UTCI), and Wet Bulb Globe Temperature Index (WBGT). The parameters required for the computation of each index are detailed in table 1.

Table 1. Required parameters to calculate thermal comfort indices.

Thermal Comfort Index	Parameters
DI	Dry bulb temperature, relative humidity
Humidex	Dry bulb temperature, relative humidity
NET	Dry bulb temperature, relative humidity, wind speed 1.2 m above ground level
PET	Dry bulb temperature, mean radiant temperature, wind speed, relative humidity, metabolic rate, clothing insulation
UTCI	Dry bulb temperature, mean radiant temperature, wind speed 10 m above ground level, relative humidity
WBGT	Wet bulb temperature, black globe temperature, dry bulb temperature

[a] Metabolic rate was set at 2 as a person walking on a level surface and clothing insulation at 0.36 for summer day clothing (walking shorts and short-sleeve shirt) [6].

[b] Wind speed measured at 1.2 and 10 m above ground level has been calculated from the logarithmic model of the vertical wind profile [7].

The Mean Radiant Temperature (T_{MRT}) was also computed using the pythermalcomfort package, following the guidelines of the ISO 7726 Standard [8]. For this calculation, a black globe diameter of 0.15 m and a black globe emissivity of 0.95 were specified.

The relative air speed (v_r) was determined as the sum of the average ambient air speed at each location and the air movement induced by human motion. This parameter was calculated using the pythermalcomfort package in accordance with the ASHRAE 55 Standard [6].

3. Results and discussion

The climatic and radiative characteristics observed in Burgos during the three measurement days are summarized in table 2. This table presents the maximum, minimum, and mean values of air temperature (T^a), wind speed (WS), relative humidity (RH), and global horizontal irradiance (GHI). These data were obtained from the meteorological and radiative station operated by the SWIFT research group, located on the roof of the Escuela Politécnica Superior Río Vena in Burgos.

Table 2. Maximum, minimum and mean values registered on the three measurement days.

Parameter	Maximum value			Minimum value			Mean value		
	19th July	21st August	27th August	19th July	21st August	27th August	19th July	21st August	27th August
T^a (ºC)	34.87	27.92	33.54	16.87	14.56	10.77	25.92	20.42	18.13
WS (m/s)	4.86	4.26	4.64	0.00	0.20	0.00	1.68	2.15	1.54
RH (%)	95.84	96.60	93.27	16.97	39.60	21.66	53.44	69.46	64.47
GHI (W/m^2)	969.20	908.29	1,138.05	0.00	0.00	0.00	348.99	302.68	253.46

Figure 2 presents the values of the six calculated indices at each of the previously mentioned locations, categorized according to their thermal stress levels throughout the measurement period.

As observed, the first two indices, DI and Humidex, do not indicate significant thermal discomfort during the early measurement hours at the three locations, with the exception of Pedro Maldonado square. At this location, the recorded data suggest that more or less 50% of individuals could experience discomfort during the measurement period. The NET classifies the thermal stress as *warm* at both measurement points in Location 1 and at Location 3 from 15:00 onward.

The last three indices—PET, UTCI, and WBGT—present higher values, as they incorporate T_{MRT} (calculated according to the ISO 7726 standard [8]) or the black globe temperature (measured directly with a black globe thermometer). Consequently, their results show stronger correlations than those of the bioclimatic indices such as DI and Humidex [9]. As a result, index values during the morning hours were higher at the Arlanzón riverbank than at the MEH esplanade (Figure 2). This discrepancy is attributed to direct solar radiation heating the black globe thermometer at the riverbank, whereas at the MEH esplanade, partial shading from a nearby tree mitigated this effect.

At Pedro Maldonado square and the heliport, the PET index reaches the *extreme thermal stress* category between 11:00 and 11:30 and between 15:00 and 18:00, respectively (Figure 2). Additionally, Klok et al. [10] found that in Amsterdam, cooling effects in areas shaded by both buildings and vegetation produced PET reductions ranging from 12 to 22ºC when compared with water bodies or green urban spaces. These values are somewhat higher than those observed in our study between Locations 1 and 3, where average PET differences of approximately 11-12ºC were recorded.

Regarding the WBGT index, which defines reference limits for various metabolic rates in both acclimatized and unacclimatized individuals according to ISO 7243 [11], all measurements at Pedro Maldonado square indicate a thermal stress levels corresponding to *very high metabolic rates* for heat-acclimatized persons. A similar pattern is observed at the heliport from 14:00 onward. While PET values were generally higher than UTCI, WBGT values were slightly lower, as shown in Figure 2 and supported by findings in [9].

The results highlight the critical role of urban shading in reducing T_{MRT}, consistent with findings from previous research [12]. Significant differences were noted at Location 3, where GHI values exceeded 600 W/m² at the heliport between 11:30 and 17:30, whereas the tree-covered area, values remained below 200 W/m² throughout the day. This strongly influences the black globe temperature readings, as the instrument's surface heats rapidly under direct solar radiation and can reach temperatures significantly higher than the ambient air. For instance, at the heliport, a black globe temperature of 46.90 °C was recorded, while the air temperature was only 32.95 °C. In contrast, this difference did not exceed 2ºC in the shaded area. This disparity may also be influenced by the surface materials at each site: the tree-covered area featured grass, whereas the heliport was paved with concrete. As demonstrated by Armson et al. [13], such surface materials significantly affect thermal conditions, although their effects are considerably reduced in shaded environments.

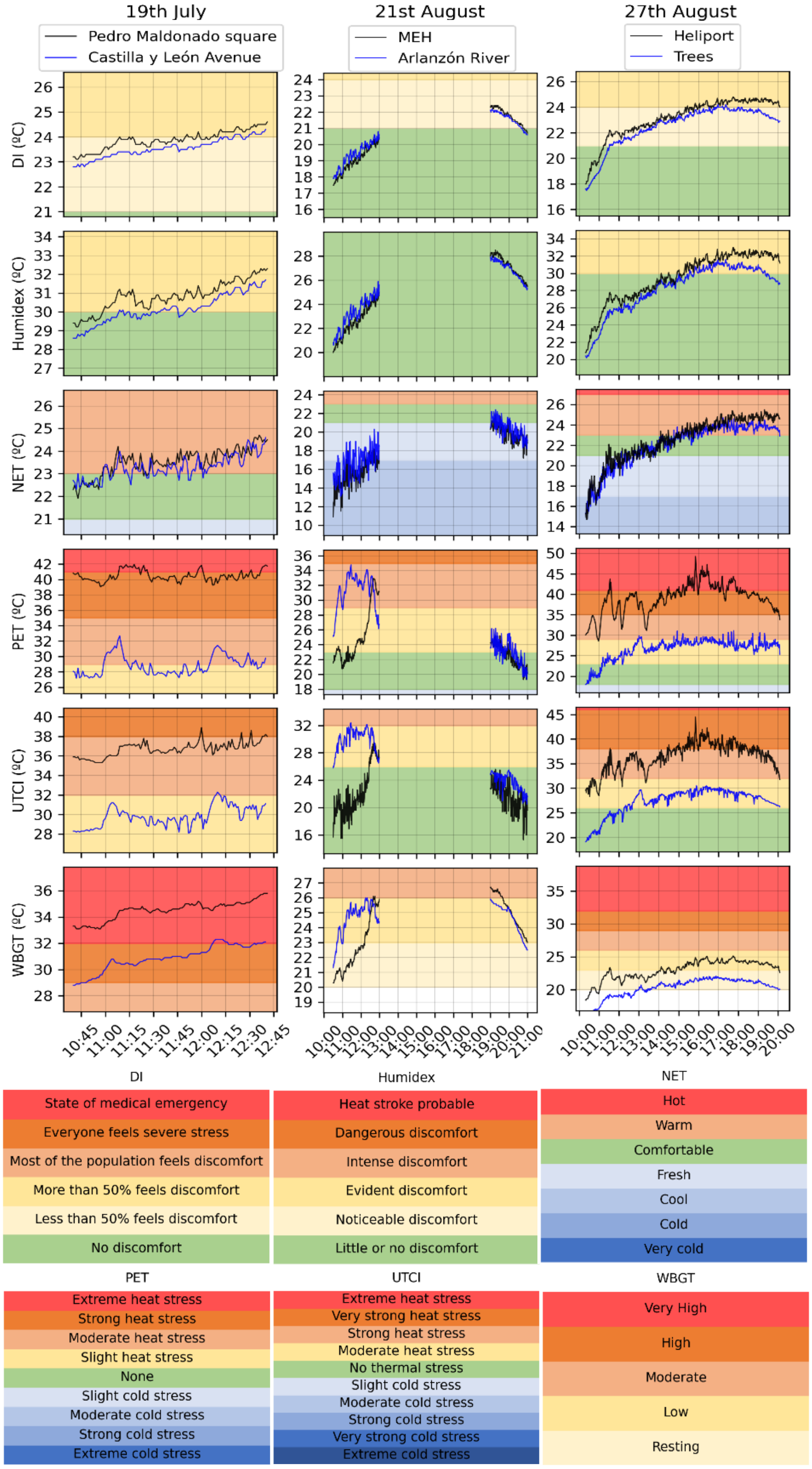

Figure 2. DI, Humidex, NET, PET, UTCI and WBGT in the three locations on 19th July (Pedro Maldonado square (black) and Castilla y León Avenue (blue)), 21st (MEH (black) and Arlanzón river (blue)) and 27th August (Heliport (black) and trees (blue)) in the city of Burgos, Spain.

4. Conclusions

This study evaluates outdoor thermal comfort in Burgos through six thermal indices across various urban settings. Results show that indices incorporating radiation, such as PET, UTCI, and WBGT, better reflect thermal stress in sun-exposed areas compared to simpler bioclimatic indices. Locations like Pedro Maldonado Square and the heliport recorded the highest thermal stress, with PET reaching extreme values and WBGT indicating high metabolic demand for acclimatized individuals.

Significant differences—up to 12 °C PET—were found between shaded and exposed environments, influenced by both vegetation and surface materials. These findings highlight the importance of incorporating green infrastructure and shading elements in urban design to mitigate heat stress and improve outdoor comfort.

The study underscores the value of localized thermal assessments and supports the implementation of climate adaptation strategies that enhance urban resilience in the face of rising temperatures.

Acknowledgements

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