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The application of the physiologically equivalent temperature to determine impacts of locally defined extreme heat events within vulnerable dwellings during the 2020 summer in Ankara

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ABSTRACT

This study addresses the limited work related to Heat Stress (HS) vulnerability within indoor/outdoor contexts and its relationship with local Extreme Heat Events (EHEs). Centred upon Ankara, the study focuses on building upon its weaker approach to human thermophysiological vulnerabilities in an era of climate change, and unregulated urban densification. Through newly defined local EHEs, the physiologically equivalent temperature (PET) (and its cumulative derivatives), were utilised to develop the limited approaches that utilise Energy Based Models in the scope of EHE risk management. The study was undertaken by processing hourly data from 2008 to 2020 from Ankara's Meteorological Station, and Esenboga Meteorological Station. At a finer 10 min resolution, an interior Kestrel Heat-stress Station was used to assess summer thermal conditions in 2020 within a thermally vulnerable, yet still very frequent, residential Turkish construction typology.

Among other outcomes, the results indicated the permanency of indoor PET that remained above 27 °C during non EHE periods. In the case of a Very Hot Day (VHD_{33}), PET remained between 29 and 32.9 °C for almost 24 h. The thermal index also indicated how forced convective cooling led to indoor reductions of PET by 3–4 K, and in duration of such HS levels to less than 2 h.

1. Introduction

Within a broader scope, the case of Ankara is representative of many other cities which need to address three interrelated aggravating issues pertaining to human thermophysiological considerations. It characterizes an urban fabric with: (i) an increasing urbanization/densification of the city centre that needs to be better controlled through urgent interdisciplinary bioclimatic understanding, planning, and management (Karaca et al., 1995; Yuksel & Yilmaz, 2008; Türkoğlu et al., 2012; Çalışkan & Türkoğlu, 2014); (ii) already high existing local Heat Stress (HS) vulnerability as a result of 'heatwave type occurrences'

Abbreviations: '*BSk*', cold semi-arid climate (-); '*Csa*', warm temperate with dry hot summer (-); '*Dsa*', snow/cold climate with dry/hot summer (-); '*Dsb*', snow/cold climate with dry/warm summer (-); $\overline{AcPETL}$, afternoon period cPETL (°C); BC, background conditions (PET = 23 °C) (-); $\overline{cPETL}$, cumulative physiologically equivalent temperature load (°C); HWE_{31}, heat wave event (#) (#); $\overline{McPETL}$, morning period cPETL (°C); MRT_I, indoor mean radiant temperature (°C); MRT_O, outdoor mean radiant temperature (°C); MTR_{20}, monthly tropical night (#) (#); $\overline{N_1cPETL}$, early night period cPETL (°C); $\overline{N_2cPETL}$, late night period cPETL (°C); oct, cloud cover (1/8); PET, physiologically equivalent temperature (°C); PET_I, indoor physiologically equivalent temperature (°C); PETL, physiologically equivalent temperature load (°C); PET_O, outdoor physiologically equivalent temperature (°C); RH_I, indoor relative humidity (%); RH_O, outdoor relative humidity (%); SU_{25}, annual summer day (#); Ta, air temperature (°C); Ta_I, indoor air temperature (°C); Ta_O, outdoor air temperature (°C); Tg_I, indoor globe temperature (°C); T_I, upper mean Ta_I limit (°C); TN_{10p}, cool nights (%); TN_{90p}, warm nights (%); TN_M, mean Ta_{Min} (°C); TN_X, Max Ta_{Min} (°C); TR_{20}, annual tropical nights (#); TX_{10p}, cool days (%); TX_{90p}, warm days (%); TX_M, mean Ta_{Max} (°C); TX_X, max Ta_{Max} (°C); $V1.1_I$, indoor air speed at 1.1m (m/s); $V1.1_O$, outdoor wind speed at 1.1m (m/s); VHD_{33}, very hot day (#); V_I, indoor air speed (m/s); V_O, outdoor wind speed (m/s); VP_I, indoor vapour pressure (hPa); VP_O, outdoor vapour pressure (hPa); WSDI, warm spell duration index (#).

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Article acronyms

AMS	Ankara's meteorological station
ASHRAE	American society of heating, refrigerating and air-conditioning engineers
CCDI	climate change detection indices
CS#	cold stress #
CTIS	climate-tourism/transfer-information-scheme
EBM	energy based model
EHEs	extreme heat events
EMS	Esenboga meteorological station
ET	expert team's
HS#	heat stress #
ICDN	indoor cooling degree necessity
IPCC	intergovernmental panel on climate change
KGC	Köppen Geiger
KHS	Kestrel heat-stress station
MEMI	Munich energy-balance model for individuals
NS	no thermal-stress
PS	physiological stress
TACs	traditional air-conditioning systems
TÜBİTAK	scientific and technological research council of Turkey
UEB	urban energy balance
UHI	urban heat island
WHO	world health organisation
WMO	world meteorological organisation

during its hot and dry summers (Demirtaş, 2018; Nouri et al., 2021); and lastly, (iii) expected augmentations of such specific vulnerabilities as a result of climate change (IPCC, 2013; Ozturk et al., 2015; Matzarakis, 2016; Ebi et al.. 2021; Matzarakis, 2021, 2022).

As determined in the study conducted by Unal et al. (2003), the encompassing Köppen Geiger Classification (KGC) for Ankara has been a topic of debate, including prior to its attributed classification of '*Dsb*' as determined by Peel et al. (2007). More recently, climatic maps prepared by Yılmaz and Çiçek (2018) revealed that while plateau areas within central/eastern Anatolian regions did present '*Dsb*' classifications, they altered to '*Dsa*' (with similar winter, albeit it drier and hotter summers) within the depressions of the Anatolian plateaus. For this reason, Ankara further presents itself as particularly interesting case study given its local temperature extremes between the summer and the winter, each presenting different local challenges upon its urban and peri-urban contexts (Nouri et al. 2021). Within the existing literature, the association of different top-down KGC assessments in connection to local bottom-up human thermophysiological conditions is one which is remains relatively unexplored. However meaningful strides have already been made, as exemplified by the study of Yang and Matzarakis (2019) who linked China's diverse KGC against different human thermophysiological conditions, and moreover linked these to national Sustainable Development Goals (SDGs). Another comparable example can moreover be found in Djamila and Yong (2016) for the case of Australia.

Considering 'heatwave type occurrences' for the case of Turkey, Unal et al. (2013) recognized the escalating occurrence in heat events trends, particularly in the southern latitudes. These outcomes were further enforced by the growing amount of research pertaining to national forest fires in the same regions (Ertuğrul et al., 2018; Ertuğrul et al., 2021). In addition, Can et al. (2019) depicted upon the relationship of HS with excess morality rates for the case of Istanbul, suggesting that: (i) research concentrating on HS related morbidity and mortality caused by heat events remains considerably limited; (ii) Turkey does not have a set of definitions to identify local Extreme Heat Events (EHEs) for different regions of the country; and lastly, (iii) the consolidation of these local definitions are moreover essential to start instituting local warning systems against urban HS susceptibility (including for the elderly and other susceptible members of the public).

Based on these factors, in addition to Turkey's considerable climatic variability (Unal et al., 2003; Öztürk et al., 2017; Yılmaz & Çiçek 2018), and the already pressing urban HS risk factors (Ozturk et al., 2015), there is a clear necessity for further research and action. As part of this initiative, was the recent constitution of identifiable, accessible, and interdisciplinary applicable EHE definitions for Ankara (Nouri et al., 2021).

As identified within the existing literature, HS effects resultant of EHEs in warming cities has been an extensive topic of study, particularly with the emergence of the climate change adaptation agenda since the turn of the century. Today, it is well documented that heat waves hold the biggest risks towards urban health as a result of their periods of unusually high sequential temperature, and the lack of night-time cooling that can last for numerous days (Matzarakis, 2022). In unison, the relationship between high urban temperatures with heat related mortality and morbidity, particularly within vulnerable settings and population groups, continues to be highlighted by the international scientific community (Ebi et al., 2021). Contiguously, the augmenting effects of global climate change upon increasing the frequency, intensity, and duration of heat extremes have also been well disseminated by international bodies as well (IPCC, 2013). These disclosed top-down assessments can be directly associated to the fact that both diurnal and nocturnal human thermophysiological loads shall augmented beyond what is already considered a public health threat (Rosenfelder et al., 2016).

It is general consensus that such contemporary approaches to EHEs have been further catalysed by the consequences of recent events, including the: (i) Chicago heatwave of 1995 leading to 706 excess deaths based upon the previous year's baseline (Tiefu et al., 1998); and, (ii) encompassing European heatwave of 2003 where the death toll exceeded 70,000 in Europe (Robine et al., 2008). These events not only highlighted the substantial consequences upon mortality rates, but moreover in: (1) the under-preparedness of urban infrastructure and health services for such disasters, including in the severe under-classification of mortality rates due to the over-exclusion of deaths on those with pre-existing medical conditions who died a heat-related death (Tiefu et al., 1998); and, (2) approaching post 'harvesting' management, which raised disputes in the distinction between deaths that were directly attributable to heat, yet also, had an already expected short life expectancy (Robine et al., 2008; Toulemon & Barbieri, 2008). Regardless of such debates, subsequent research highlighted that such differentiations would become less significant as the quantity of annual days witnessing EHEs would eventually lead to one 'long heat wave summer' (Hayhoe et al., 2010).

Subsequent European EHEs in following years (such as 2015, 2017, 2018, and 2019) continued to unravel the strong association to climate change effects, both in their capacity to augment EHE intensity and likelihood (Vautard et al., 2019). In 2020, unanticipated latitudes such as the northern region of Siberia marked a noteworthy prolonged heating period with anomalously high temperatures that were deemed virtually impossible without the effect of global climate change (Ciavarella et al., 2021).

The disclosed consensus has further propagated studies to approach warning, handling, and preventing strategies and measures within urban fabrics. Within the contemporary consolidated fabric, the movement to subsequently address both existing and projected increases in EHE frequencies, durations, and intensities (e.g., in Kovats and Ebi 2006, Matzarakis 2016, Nouri et al. 2018, Matzarakis 2021).

Centred upon the case of Ankara, Nouri et al. (2021) developed an initial air temperature (Ta) based Indoor Cooling Degree Necessity

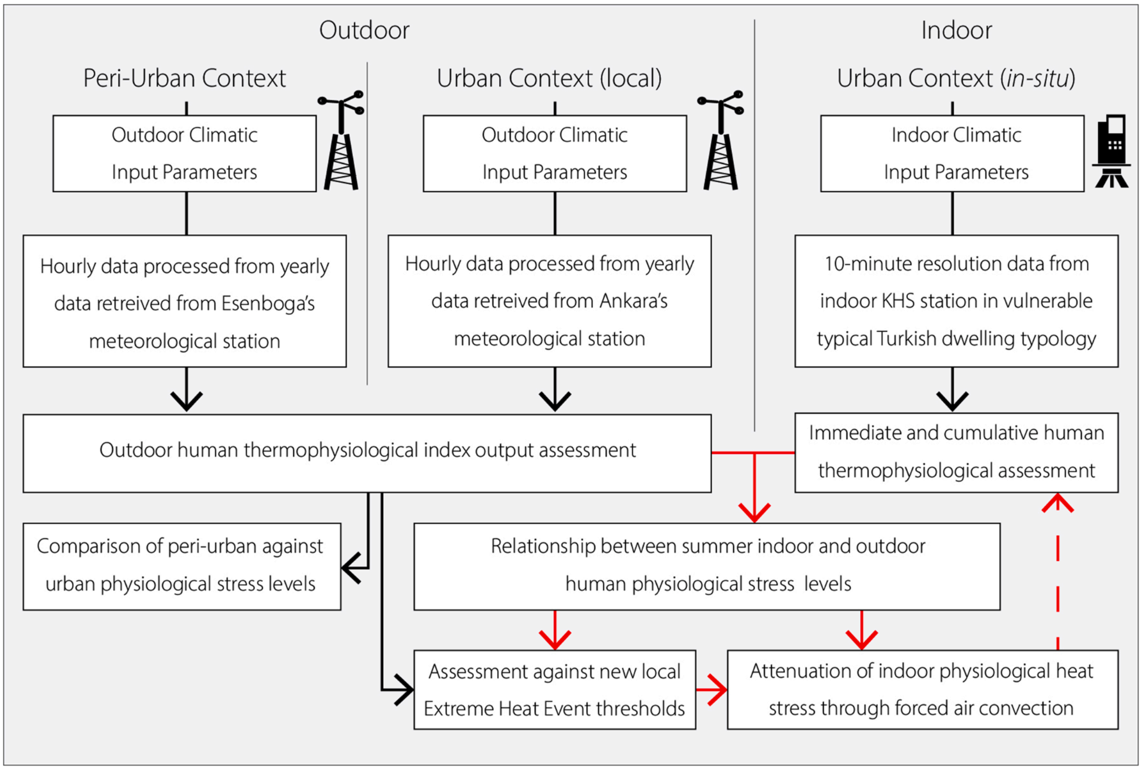

Fig. 1. Research methodology framework showing the collection and processing of both outdoor and indoor climatic parameters to determine human thermo-physiological risk factors and attenuation possibilities.

(ICDN) metric centred upon a frequent yet vulnerable residential construction typology (Esiyok, 2006; Gültekin & Farahbakhsh, 2016). In addition, the ICDN was moreover correlated to newly constructed EHE definitions for Ankara by utilising and adapting the WMO's Expert Team's (ET) temperature core Climate Change Detection Indices (CCDI) (Peterson et al., 2001).

While using the stipulated local EHEs, the initial ICDN approach was taken a step further in this research to both examine and attenuate the effects of heat upon human biometeorological thermoreceptors. Given the limited amount of existing studies that approach *in-situ* human thermophysiological thresholds both indoors and outdoors to assess impacts of heat intensities and frequencies (Basu & Samet, 2002; Nastos & Matzarakis, 2008; Nazaroff, 2008; White-Newsome et al., 2012), this study addresses such a gap in the literature, furthermore during identified local EHEs.

To realise this assessment, an Energy Based Model (EBM) index was utilised to assess the immediate and cumulative loads upon the human biometeorological system. More concretely, the physiologically equivalent temperature (PET) (Mayer & Höppe, 1987; Höppe, 1999; Matzarakis et al., 1999) was utilised to examine the distribution of Physiological Stress (PS) thresholds as originally presented by Matzarakis and Mayer (1997).

According to the study by Freitas and Grigorieva (2015), and corresponding to the limited 'G' category, the PET index falls upon within EBM stress classification. Such a category accommodated indices which, although involved more calculation routines (in comparison to those from other simpler index categories), presented the best performing indices pertaining to the body-atmosphere balance variety (Freitas & Grigorieva, 2016). Although constructed upon a slightly divergent evaluation methodology, from 165 thermal indices, Staiger et al. (2019) further highlighted the application suitability of four EBM indices. Of these few, PET was further highlighted for its applicability for thermal evaluations within bioclimatic orientated assessments, as also highlighted by other relevant studies (e.g., Cohen et al., 2012; Nouri, 2013; Abreu-Harbich et al., 2015; Martinelli et al., 2015; Algeciras et al., 2016; Chatzidmitriou & Yannas, 2017; Lin et al., 2017; Nouri & Costa, 2017a; Nouri et al., 2018; Staiger et al., 2019).

In addition, processed climatic input variables (i.e., indoor air speed (V_I)) were subsequently also modified to determine the thermophysiological effects that forced convective cooling can have upon human thermoreceptors. This provided a means to quantitatively evaluate how to lower PS during periods of accentuated HS, without the reliance on counterintuitive Traditional Air-Conditioning systems (TACs). Such evaluations of human thermophysiological conditions were undertaken through different temporal scopes/resolutions, which enabled assessments to determine both immediate and temporally cumulative thermal vulnerabilities. The latter was approached using an adaptation of the initial PET derivative as determined by Charalampopoulos, Tsiros et al. (2016) to investigate HS effects during four predetermined periods of the day.

Albeit based more upon the qualitative side of thermal comfort conditioning, the potential and/or positive effects of increasing $V1.1_I$ to counteract elevated Ta_I levels in broadening overall indoor thermal acceptability ranges has been well established since well before the turn of the century (e.g., Fanger, 1973; Gagge et al., 1986; Fountain & Arens, 1993). Today, the current literature continues to show that higher Ta_I of up to 28 - 30 °C can be considered part of the 'thermally acceptable' range with the use of fans that induce higher $V1.1_I$ speeds (He et al., 2019). Moreover, within a subsequent study, He et al. (2020) further determined that: (i) in the absence of an available ceiling fan, users would 'by default' utilise AC units to reduce Ta_I down to 25.7 °C; and, (ii) with the presence of a continuously operating ceiling fan, the test subjects demonstrated a considerably higher thermal acceptability of Ta_I (ranging between ≈ 28 and 29 °C). While different speeds were utilised within the study, in settings with higher temperatures, users tended to set V_I at 1 m/s. In association, comparable outcomes were attained by ASHRAE (2017) in similar conditions, where respective the 'thermal acceptability' of respondents could be extended by ≈ 3 °C within a V_I

Table 1
Indoor and outdoor meteorological station stipulation, single variable collection and temporal resolution.

	Outdoor Collection Methodology				Indoor Collection Methodology	
Data Typology	Urban		Peri-Urban		*In-situ*	
Temporal Data Scope	Yearly (-)		Yearly (-)		Monthly (2020)	
Datasets	[2008..2020]		[2008..2020]		[7,8]	
Data Resolution	1 h		1 h		10 min	
Station & Variables	AMS (Ankara MS (AMS))		EMS (Esenboga MS (EMS))		KHS (Kestrel HS (KHS))	
	Var.	Unit	Var.	Unit	Var.	Unit
	Ta_O	[°C]	Ta_O	[°C]	Ta_I	[°C]
	V_O	[m/s]	V_O	[m/s]	$V1.1_I$	[m/s]
	RH_O	[%]	RH_O	[%]	RH_I	[%]
	VP_O	[hPA]	VP_O	[hPA]	VP_I	[hPA]
	Oct	[1..8]	Oct	[1..8]	Tg	[°C]

speed of 1 m/s.

While such studies remain an integral side of thermal comfort in terms understanding human qualitative behavioural and psychological responses, they cannot substitute the quantitative side to human biometeorological understanding in such processes (or vice-versa). As defined by Höppe (1999) the human biometeorological system lacks selective sensors that would otherwise enable the perception of individual climatic parameters. Instead it can only determine (through thermoreceptors) and make a thermoregulatory response to the encircling temperature.

In turn and when considering 'preventative approaches' towards urban thermal risk factors (including HS), one must also consider other encircling climatic parameters in quantitative terms. Beyond Ta, these include Relative Humidity (RH), air/wind speed (V), and radiation fluxes to determine the quantitative thermophysiological effects on humans within either within indoor and outdoor contexts (Matzarakis 2020). The existing literature has also underlined that these variables enable a more detailed comprehension regarding the interface with human thermoregulation dynamics (Hensel & Schafer, 1984; Katić et al., 2016), and how the biometeorological system itself is approached (Höppe, 1984, 1993; Giannaros et al., 2018; Christen, 2020).

Such a 'human-centred approach' builds upon the acknowledged limited literature/methodologies to record, approach, and manages PS between outdoor and indoor contexts. This includes tackling the temporal resolution between both of these 'separate-yet-related' contexts. This disclosed relationship, while imperative, is one that has witnessed limited attention, including within studies that assess heat-related morbidity and mortality using only outdoor temperature from meteorological stations (Basu & Samet, 2002; Santamouris, 2014; Santamouris et al., 2016).

To effectively consolidate such cross-structures and understanding (particularly in an era of augmenting EHEs in densifying cities), the balance with indoor human thermophysiological conditions must thus be further solidified to better define, and regulate, urban human PS vulnerability. Aiming to also extract novel lessons for other cities as well, the warming capital of Ankara will be approached as a case study to build upon the existing literature in making contemporary cities more thermally resilient and sustainable in an era of climate change through a 'human-centred approach'.

2. Materials and methods

2.1. Data collection

To conduct the study, different meteorological stations were utilised to retrieve and process the climatic conditions at different temporal timeframes and resolutions. This was undertaken to both determine conditions during the summer of 2020, and further, contextualise such results with previous years. The methodical framework of the study is illustrated in Fig. 1.

For outdoor assessments, data was collected and processed at a 1 h resolution using Ankara's Meteorological Station (AMS), and from its peri-urban Esenboga Meteorological Station (EMS). Through the use of the EBM index, the use of the two outdoor MSs further permitted the comparison between peri-urban and urban bioclimatic conditions. In tallying to the abovementioned stations, and based upon the application PET index, indoor microclimatic variables were collected/processed using an *in-situ* Kestrel Heat-stress Station (KHS) configured to a finer 10 min resolution during the months of July and August from the summer of 2020.

As illustrated in Table 1, the input parameters retrieved from the three meteorological stations that were collected at the different temporal scopes and resolutions. Both the outdoor stations collected data at an hourly rate between 2008 and 2020 for two purposes: (1) to compare and contextualise the biometeorological results undertaken during the 2020 summer period with previous years; and, (2) to continue to utilise the previously calculated CCDI's from the AMS, and cross-examine the EBM index outputs against the locally defined EHE thresholds.

In contrast to the study by Nouri et al. (2021) that focused upon the establishment of an Ta_I focused ICDN metric for thermally vulnerable dwellings, this study takes this evaluation a step further. More specifically, with the interest upon evaluating PS thresholds centred upon human biometeorological standards, the methodology utilised in this study utilises a novel methodical approach. Expanding on the Ta_I based ICDN it firstly represents a method to assess human thermophysiological risk periods, intensities and durations. Secondly, it presents approaches to attenuate such thermal stimulus upon the human biometeorological system through indoor convective cooling.

2.2. Climatic variables

2.2.1. Outdoor variables

To construct the EBM assessment, five climatic variables were retrieved from both indoor and outdoor meteorological stations. For the AMS and EMS stations, a total of twenty-four recordings at an hourly interval were collected to determine diurnal/nocturnal fluctuations between the years of 2008 and 2020. The selection of these variables was based upon their crucial role in determining the impact upon the human biometeorological system as a result of encircling environmental circumstances (Parsons, 2003; Cohen et al., 2013; Binarti et al., 2020).

The outdoor variables retrieved from the AMS and EMS stations were air temperature (Ta_O), relative humidity (RH_O), vapour pressure (VP_O), wind speed (V_O), and cloud cover (Oct). With regards to the latter two, the study included wind dynamics and radiation fluxes given their crucial role in the scope of bottom-up thermal comfort studies (Matzarakis & Amelung, 2008; Lin, 2009; Hwang et al., 2010; Algeciras & Matzarakis, 2015; Matzarakis et al., 2016; Nouri & Costa 2017a; Charalampopoulos, 2019).

Given that the AMS and EMS stations recorded V_O considerably higher than of pedestrian height, it needed to be adapted beforehand to certify that such measurements were applicable to gravity centre of the human body. As a result the original values were adapted to a height of 1.1 m from the ground through the application of the formula as defined by Kuttler (2000):

$$V1.1_O = V_h^* \left(\frac{1.1}{h}\right)^{\alpha} \qquad \alpha = 0.12^* z_0 + 0.18 \tag{1}$$

where: V_h is the m/s at a height of h (10 m), α is an empirical exponent, depending upon urban surface roughness, and Z_0 is the analogous roughness length.

According to the general urban morphological composition of Ankara's urban fabric, α was configured at a value of 1.5. The resulting calibrated V_O values were henceforth expressed as $V1.1_O$. Furthermore, and with regards to accounting for radiation fluxes, Oct values were

Table 2
Specifications of Kestrel Heat Stress 5400 (KHS) station.

#	Climatic Variable	Accuracy	Resolution	Specification Range
(1)	Air Temperature (Ta_I)	0.5 °C	0.1 °C	-29.0 to 70.0 °C
(2)	Wind/Air Speed ($V1.1_I$)	> of 3% of reading	0.1 m/s	0.6 to 40.0 m/s
(3)	Relative Humidity (RH_I)	2%	0.1 %	10 to 90% (25 °C noncondensing)
(4)	Vapour Pressure (VP_I)	1.5 hPa / mbar	0.1 hPa / mbar	700-1100 hPa / mbar (25 °C)
(5)	Globe Temperature (Tg_I)	1.4 °C	0.1°C	-29.0 to 60.0 °C

Table 3
Grade extension of Physiological Stress (PS) on human beings to accompany increased values beyond the physiologically equivalent temperature (PET) value of 41 °C in light of projected estimates | Source: adapted from Matzarakis et al. (1999) and Nouri et al. (2021).

PET[*1] (°C)	PS Level	Stress Level Abr.		Existing/Added
0 ~4	Extreme Cold Stress	Cold Stress	(CS4)	Existing
4 ~8	Strong Cold Stress		(CS3)	Existing
8 ~13	Moderate Cold Stress		(CS2)	Existing
13 ~18	Slight Cold Stress		(CS1)	Existing
18 ~23	No Thermal Stress	(-)	(NS)	Existing
23 ~29	Slight Heat Stress	Heat Stress	(HS1)	Existing
29 ~35	Moderate Heat Stress		(HS2)	Existing
35 ~41	Strong Heat Stress		(HS3)	Existing
41 ~46	Extreme Heat Stress		(HS4)	Added
> 46	Beyond Extreme Heat Stress		(HS5)	Added

[*1] Ranges of PS for PET calculation based upon an internal heat production of 80 W, and a heat transfer resistance of the clothing set to a value of 0.9 clo according to Matzarakis and Mayer (1997)

processed in combination with the abovementioned climatic variables to obtain MRT_O estimations at an hourly resolution. Such an approach enabled the research to determine the radiative exchange from the encircling environment with the human thermophysiological system.

2.2.2. Indoor variables

At a finer measurement resolution of 10 min for the months of July and August during the summer of 2020, all five of the outdoor variables were also recorded indoors by the KHS (Table 2), with the exception for Oct, which was replaced with indoor Globe Temperature (Tg_I). Subsequently, and in addition to Ta_I, Tg_I was utilised to calculate MRT_I using the formula as defined by the ISO-7726 (1998):

$$MRT_I = \left[(Tg_I + 273)^4 + \frac{0.25 \times 10^8}{\varepsilon} \left(\frac{|Tg_I - Ta_I|}{D} \right)^{1/4} \times (Tg_I - Ta_I) \right]^{1/4} - 273 \tag{2}$$

where: Tg_I is indoor Globe Temperature, Ta_I is indoor Air Temperature, $D = 0.025$ m, and $\varepsilon = 0.95$ (i.e., matt black)

As recognised in Nouri et al. (2021), there was limited oscillation between indoor Ta_I and Tg_I during the study period of July and August. Nevertheless, taking radiation fluxes into more consideration, in addition to similar assessments undertaken outdoors, the variation extent of such variables was moreover determined in this study. The disclosed approach further highlights the crucial heat exchange dynamics via radiative exchange with indoor contexts (Marino et al., 2018).

2.3. Thermophysiological EBM index

To both quantitatively estimate and modify human PS thresholds as originally determined by Matzarakis et al. (1999) the EBM PET index was utilised. Configured upon the Munich Energy-balance Model for Individuals (MEMI) (Höppe, 1984, 1993), it is defined by the Ta_I at which, in a typical indoor setting, the human energy budget is maintained by skin temperature, core temperature, and perspiration rate are equivalent to those under the assessed conditions. Using the aforementioned climatic variables (for both indoor and outdoor settings, including $MRT_{I/O}$) as input parameters, the PET was calculated via the human biometeorological model, RayMan Pro (Matzarakis et al., 2007, 2010; Matzarakis & Fröhlich, 2018; Fröhlich et al., 2019).

In addition to the aforementioned reasons, and specific to this research, the decision to utilise the PET index is attributed to its: (i) facility of calibration using easily accessible climatic input variables, and, (ii) its base measuring unit being in °C, thus simplifying their interpretation for non-climatic experts, including architects, urban planners and designers who play a crucial role in applying such information within both indoor and outdoor contexts. Finally, based upon the inherent 'human-centred approach', the (Indoor/Outdoor) PET $_{(I/O)}$ results were directly related to the aforementioned PS grades as disclosed in Table 3. Thus far, numerous studies have discussed the relationship/calibration of thermophysiological indices against their originally designated PS thresholds (e.g., Hwang & Lin, 2007; Lin & Matzarakis, 2008; Lin, 2009; Matzarakis, 2014a; Nouri et al., 2018; Potchter et al., 2018; Nouri et al., 2021). Similarly, and with regards to outdoor conditions recorded by the AMS and EMS, the study proposed an extension to the original grades pertaining to the levels of HS beyond the original 'Extreme Heat Stress' threshold. Here, and constructed upon the previous investigative 'What if?' approach to assess human biometeorological implications within extreme environmental conditions as conducted in Nouri et al. (2018), two new grades established beyond the original threshold of > 41 °C. The respective grades were based upon an increment of roughly 5 °C per physiological threshold. As they were the fourth and fifth levels of HS after the 'No thermal Stress' (henceforth NS), these new grades were respectively designated as HS4 and HS5 according to the stress level abbreviation system, depicted in Table 3.

Additionally, a further analysis was undertaken to directly account for indoor/outdoor instantaneous of PET Load (PETL), and lengthier cumulative PETL (cPETL) values. Such derivatives from the PET index were produced by Charalampopoulos et al. (2016) for outdoor contexts, where: (i) PETL refers to the variation from optimum conditions (henceforth termed Background Conditions (BC)), thus enabling the determination of a specific value of immediate excess thermophysiological stress (Eq. (3)); and, (ii) cPETL which determines the cumulative total sum of PETL during a sequence of predetermined hours.

$$PETL = PET_{Min.X} - BC \tag{3}$$

where: $PET_{Min.X}$ is the PET value at minute 'X', and Background Conditions (BC) in this study was set to denote the maximum PET for the PS grade of 'No thermal stress' (i.e., of 23°C)

In this study, the application of cPETL was configured a little differently based upon two principal adaptations. Firstly, rather than determining the summation of total hourly PETL, the summation instead was derived from the average PETL values for the specified time period. In this way, and associated to the second modification, the summation values of the $\overline{cPETL}$ (Eq. (4)) enabled the comparison of average values for: (i) shorter assessment periods; and, (ii) between outdoor (based on 1-hour resolution) and indoor (based on 10 min resolution) measurements, which as presented in Table 1, were recorded at different temporal resolutions. Resultantly, and in the interest of standardisation with the measurements processed from the AMS/EMS, the same temporal resolution was applied to the KHS outputs.

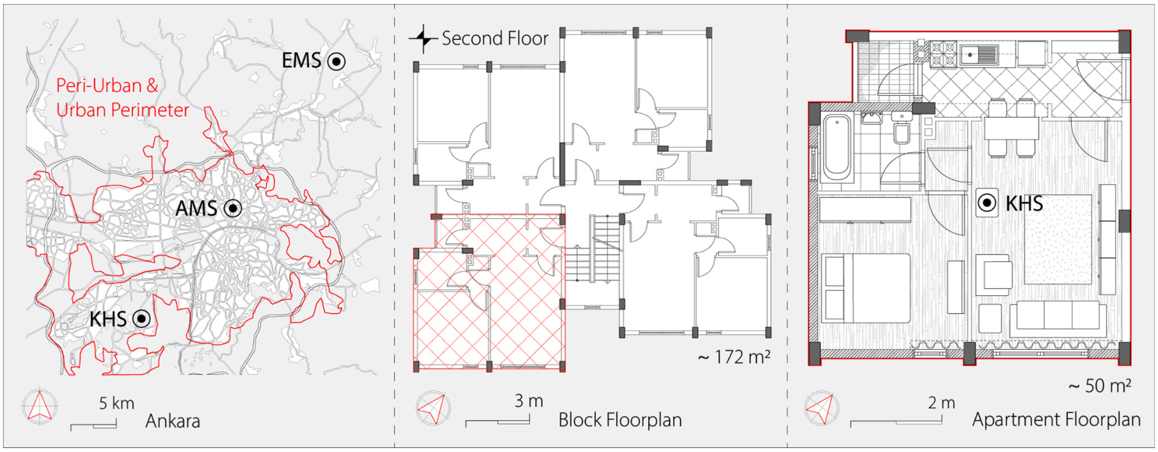

Fig. 2. Outdoor and indoor locations of the different utilised meteorological stations, case study block and apartment floorplans with relevant floor areas within Ankara's urban centre perimeter.

$$\overline{\text{cPETL}} = \frac{1}{n}\sum_{h}^{n}\text{PETL} \tag{4}$$

where: average cumulative PET Load ($\overline{\text{cPETL}}$) is calculated based upon the sum of the retrieved averages for different predetermined 6 h periods of sequential PETL, defined by: n = the upper limit hour; and, h = serving as the respective commencement hour as detailed in Eq. (5).

$$\overline{\text{N}_1\text{cPETL}} = \frac{1}{6}\sum_{h=0}^{6}\text{PETL} \quad \overline{\text{McPETL}} = \frac{1}{12}\sum_{h=6}^{12}\text{PETL}$$
$$\overline{\text{AcPETL}} = \frac{1}{18}\sum_{h=12}^{18}\text{PETL} \quad \overline{\text{N}_2\text{cPETL}} = \frac{1}{23}\sum_{h=18}^{23}\text{PETL} \tag{5}$$

where: $N_1 \triangleq$ Early Night Period (00:00–05:50), M $\triangleq$ Morning Period (06:00–11:50), A $\triangleq$ Afternoon Period (12:00–17:50), $N_2 \triangleq$ Late Night Period (18:00–23:50)

As determined in Eq. (5), four temporal periods, each with a duration of almost 6 h, these being: (1) Early Night Period (N_1), running between 00:00 and 05:50; (2) Morning Period (M), running between 06:00 and 11:50; (3) Afternoon Period (A), running between 12:00 and 17:50; and, (4) Late Night Period (N_2), running between 18:00 and 23:50). In comparison to coarser temporal periods (e.g., diurnal and nocturnal), such a methodology further permitted the analysis of more detailed cumulative thermophysiological thresholds/patterns, i.e., during two diurnal and two nocturnal periods.

Within this case, the variation of temporal resolutions between the different derivatives of the EBM index, were hence related to: (i) instantaneous PET or PETL calculations (based on 24 h measurements a day from the AMS/EMS, or 144 measurements a day at a 10 min interval form the KHS); or (ii) longer cumulative assessments which enabled a different perspective into how excess HS (or lack of) could be identified within a specified window of accumulated hourly measurements. Adjacently, this stipulated quantitative evaluation of the thermophysiological conditions (both for outdoors and indoor conditions) were concomitant with approach recently highlighted by Matzarakis (2021) in terms of both data resolution and processing.

2.4. Local EHE definition for Ankara

Within the aforementioned ICDN study undertaken by Nouri et al. (2021), local EHE definitions were established for Ankara's city centre by employing and modifying the WMO's ET CCDIs (Peterson et al., 2001). Such an assessment was undertaken using the hourly data retrieved from the AMS and processed through the R-based package, RClimDex (Zhang & Yang, 2004). The applied methodology utilised to tackle the specific case of Ankara's EHEs was based upon the use of twelve Ta_O based core CCDIs, which were subsequently divided into six groups as summarised in Appendix A.

While it is documented that the principal objective of the CCDI is to identify climate change trends over a temporal period of thirty years, as identified in the aforementioned study with regards to Ankara, the only station with sufficient data (in terms of complete yearly/hourly data) was the peri-urban EMS. However, as previously identified in local studies (e.g., Çalışkan & Türkoğlu, 2014; Nouri et al., 2021), bioclimatic conditions are to divergent to then accurately determine HS levels within the city centre if based from the EMS datasets.

Although the AMS was more restricted, the predominantly uninterrupted data from 2008 onwards was sufficient to: (i) contextualise the results of the study with proceeding years; and, (ii) undertake the required percentile studies through the RClimDex to establish the first set of definitions of local EHEs for Ankara. The initial calculation procedure as defined by Zhang et al. (2004) was utilised to define occurrences of Cool Days/Nights, Warm Days/Nights, and the Warm Spell Duration Index. Nevertheless, given the focus upon local thresholds for Ankara through the application of the CCDIs, it was possible to further calibrate these definitions configured upon local 90th and 95th percentiles. Based upon hourly recorded Max Ta_{Max} (i.e., TX_X) values between 2008 and 2020, the respective fixed temperature thresholds of 31 and 33 °C were stipulated. Resultantly, it was possible to identify the occurrence of: (1) Very Hot Days (VHD_{33}), where TX_X exceeded 33 °C; and, (2) in alignment with temporal period of the WSDI, and with common heatwave definition practice identified in Piticar et al. (2019), a Heat Wave Event (HWE_{31}) when TX_X exceeded 31 °C for six sequential calendar days. As a result, this implied that if during the summer the TX_X did not meet either upper thresholds, it would considered a typical Summer Day (i.e., SU_{25}), as long TX_X surpassed that of 25 °C as stipulated by Zhang & Yang, 2004. Lastly, Monthly Tropical Nights (MTR_{20}) was also added to ascertain days where temperature surpassed 20 °C, only based instead upon Max Ta_{Min} (i.e., TN_X) given the handling of nocturnal temperatures.

2.5. Residential case study description

To relate the EBM results of this study with those of the aforementioned ICDN study, the same residential case study was utilised. The selection of the case study was based upon the assessment of a stereotypical representation of Turkish residential construction methods that have yet to be updated to current building regulation norms (Gültekin & Farahbakhsh, 2016).

This type of reinforced concrete structure system, entailing hollow clay brick external/internal walls finished with cement plaster and a

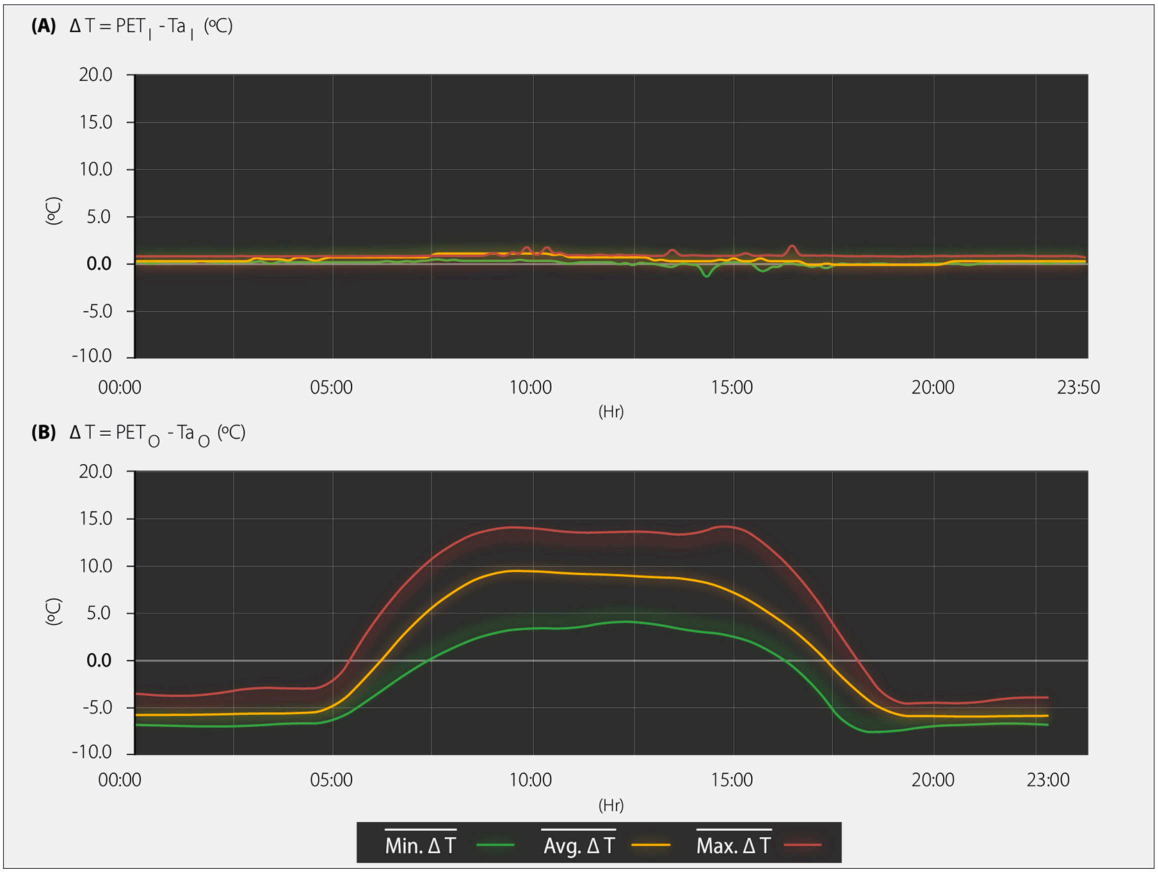

Fig. 3.. (A) Average variation between PET_I and Ta_I indoors at a temporal resolution of 10 min between July and August 2020 | (B) Average variation between PET_O and Ta_O outdoors at a temporal resolution of 1 h between July and August 2020.

load-bearing skeleton without any outer shell insulation, still remains very common within Turkey (Esiyok, 2006). Resultantly, the naturally ventilated residential unit, demonstrated in Fig. 2, constructed during the 1980's as part of the constitution of Bilkent University represented an effective setting to evaluate indoor vulnerability to locally defined EHE thresholds.

2.6. Variable modification

Via the EBM index, it was possible to furthermore assess how the modification of climatic variables could influence overall PS exposure during respective periods of elevated HS. More specifically, through the use of the PET index within this subsequent study, it was possible to investigate how an augmentation of 1 m/s in $V1.1_I$ could quantitatively influence human PS thresholds, particularly during periods of identified accentuated HS.

Resultantly, in addition to the original indoor PET assessment for the summer months of 2020 (Table 1), the KHS data was processed once again through the RayMan model (Fig. 1). The objective of this assessment was to determine the extent that forced convection through air movement can physiologically have upon the aforementioned human thermoreceptors when encompassing Ta_I levels remained unaltered.

2.7. Statistical analysis and output representation methods

Before assessing the thermophysiological outputs, the average hourly minimum, average, and maximum deviations between the climatic variables were determined to: (1) establish the variation extents between $\overline{Ta}$ and $\overline{PET}$ both indoors and outdoors; and, (2) compare the variation extents between $\overline{MRT_I}$ and $\overline{MRT_O}$, $\overline{Ta_I}$ and $\overline{Ta_O}$, $\overline{V1.1_I}$ and $\overline{V1.1_O}$, and lastly, $\overline{RH_I}$ and $\overline{RH_O}$. By determining such statistical patterns related to the average variation extents during day, the symbiotic relationship amid the variables and moreover, between the two types of settings, could be investigated.

After the Heatmap outputs, the human thermophysiological outdoor results for July and August 2020 were compared with those of the previous century for Ankara. Such a statistical assessment was undertaken by examining the daily distribution of minimum, average, and maximum $\overline{PET_O}$ values from both the peri-urban EMS and urban AMS, and relating these outcomes with the respective PS grades as presented in Table 3.

It was important in the study to accommodate the growing interdisciplinary necessity to ensure the easy interpretation of research results. This implied the fortification of interdisciplinary bridges with other professionals who shall play an equally important role in addressing how urban fabrics can be shaped around such growing concerns associated to climate (Nouri et al., 2018; Lopes et al., 2021). For this reason, the human thermophysiological outputs were presented via two predominant methodologies.

Firstly, and subsequent to the graphs illustrating indoor-outdoor variable differentiations, Heatmaps were produced to present outdoor/indoor PET, and their resulting PS thresholds. In alignment with the rational as disclosed by Charalampopoulos (2020), the decision to utilise the Heatmaps correlates to the growing use of 'R' within urban biometeorological studies including the reading and interpretation of their results. Resultantly, the Heatmaps were constructed through R-Script as a means to facilitate the readability and communication of the outputs through the use of 'dplyr' (Wickham, François, & Henry, 2020), 'reshape2' (Wickham, 2007), and 'lubridate' (Grolemund & Wickham, 2011) packages, in addition to 'plotly' (Sievert, 2020) for the

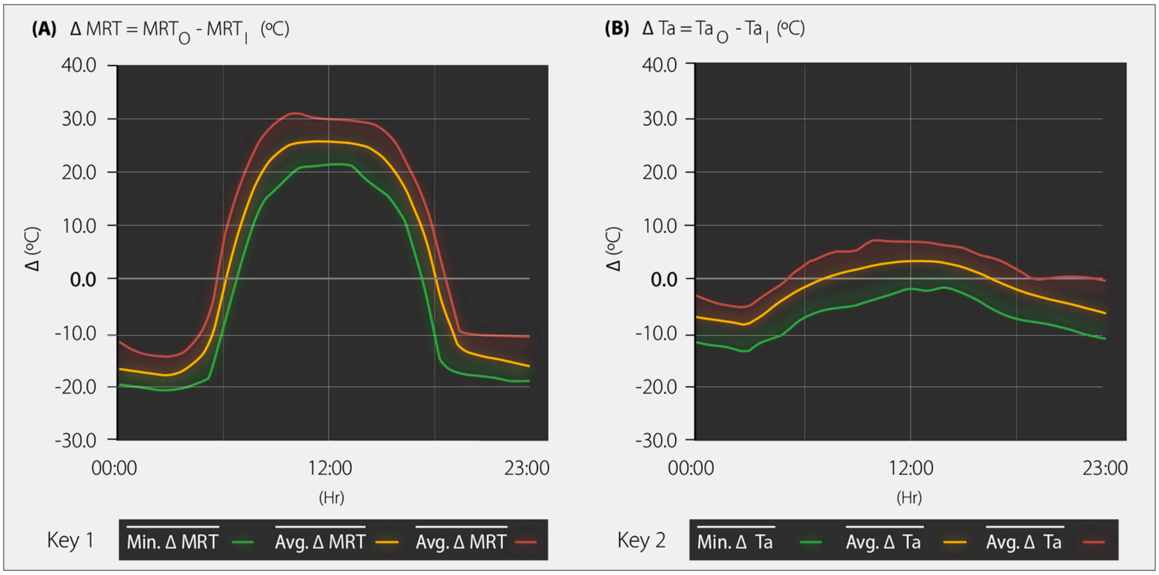

Fig. 4. (A) Average variation between MRT_O and MRT_I at a temporal resolution of 1 h between July and August 2020 | (B) Average variation between Ta_O and Ta_I at a temporal resolution of 1 h between July and August 2020.

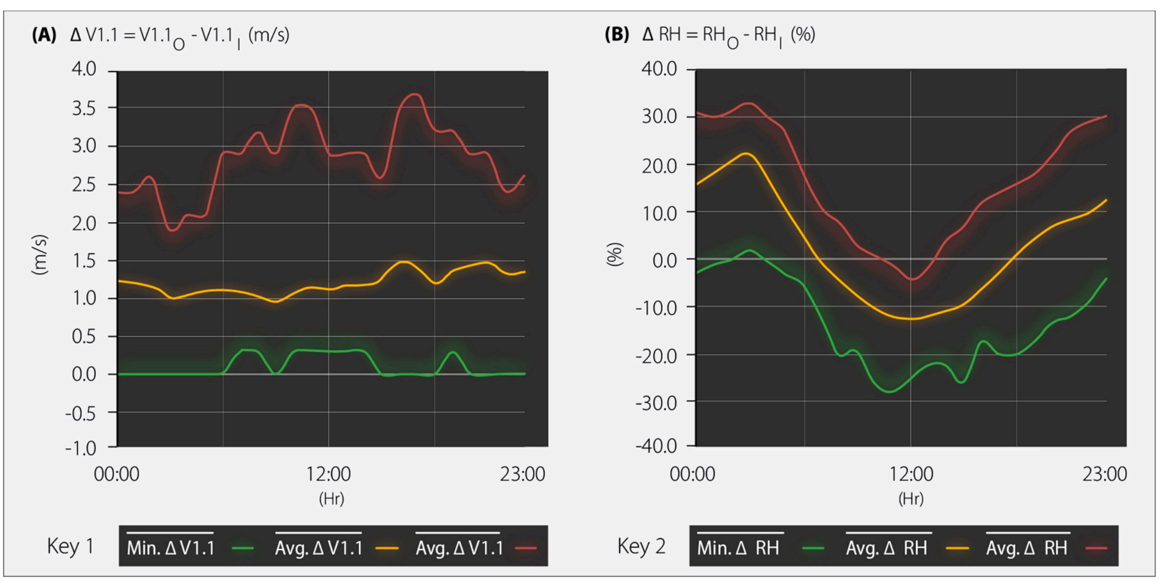

Fig. 5. (A) Average variation between $V1.1_O$ and $V1.1_I$ at a temporal resolution of 1 h between July and August 2020 | (B) Average variation between RH_O and RH_I at a temporal resolution of 1 h between July and August 2020.

visualisation.

Secondly, the PETL outputs from the research were presenting using the Climate-Tourism/Transfer-Information-Scheme (CTIS) model (Matzarakis, 2014b), a frequent communication method utilised within the international community within climatic and biometeorological studies (e.g., Herrmann & Matzarakis, 2012; Lin et al., 2015; Algeciras et al. 2016; Nouri et al., 2017). Resultantly, it was possible to represent the human thermophysiological fluctuations at different temporal resolutions for the outdoor and indoor conducted in the study (i.e., at a 1 h, and a 10 min resolution, respectively).

3. Results

3.1. Average indoor-outdoor variable oscillations

As shown in (Fig. 3), given the much lower vulnerability to variables such as radiation fluxes, differences were a lot lower indoors between $\overline{PET_I}$ and $\overline{Ta_I}$, with a $\overline{\text{Min. }\Delta}$ of -0.7 K, a $\overline{\text{Max. }\Delta}$ of 2.4 K, and an $\overline{\text{Avg. }\Delta}$ which did not surpass 0.6 K. Such a result enforces the much stronger association between the EBM index outputs with Ta_I. Accordingly, the oscillation amid the hourly averages between $\overline{PET_O}$ and $\overline{Ta_O}$ were considerably greater with a recorded a $\overline{\text{Min. }\Delta}$ of -7.5 K at 18:00, and a $\overline{\text{Max. }\Delta}$ of 14.8 K at 15:00.

When considering the oscillation of the other measured variables, it was possible to further corroborate the results identified within Fig. 4. In the case of $\overline{MRT_I}$, it varied between 25.4 °C at 06:00 and 32.4 °C at 15:00. This was contrasted with the $\overline{MRT_O}$ that presented higher oscillations. As a result, Fig. 4(A) presented clear relationships with sunrise and sunset periods, with: (i) $\overline{\text{Min. }\Delta}$ ranging between -21.4 °C and -17.7 °C during the night; and, (ii) $\overline{\text{Max. }\Delta}$ oscillating between 30.2 °C at 09:00, and 28.3 °C at 15:00. The comparison between $\overline{Ta_O}$ and

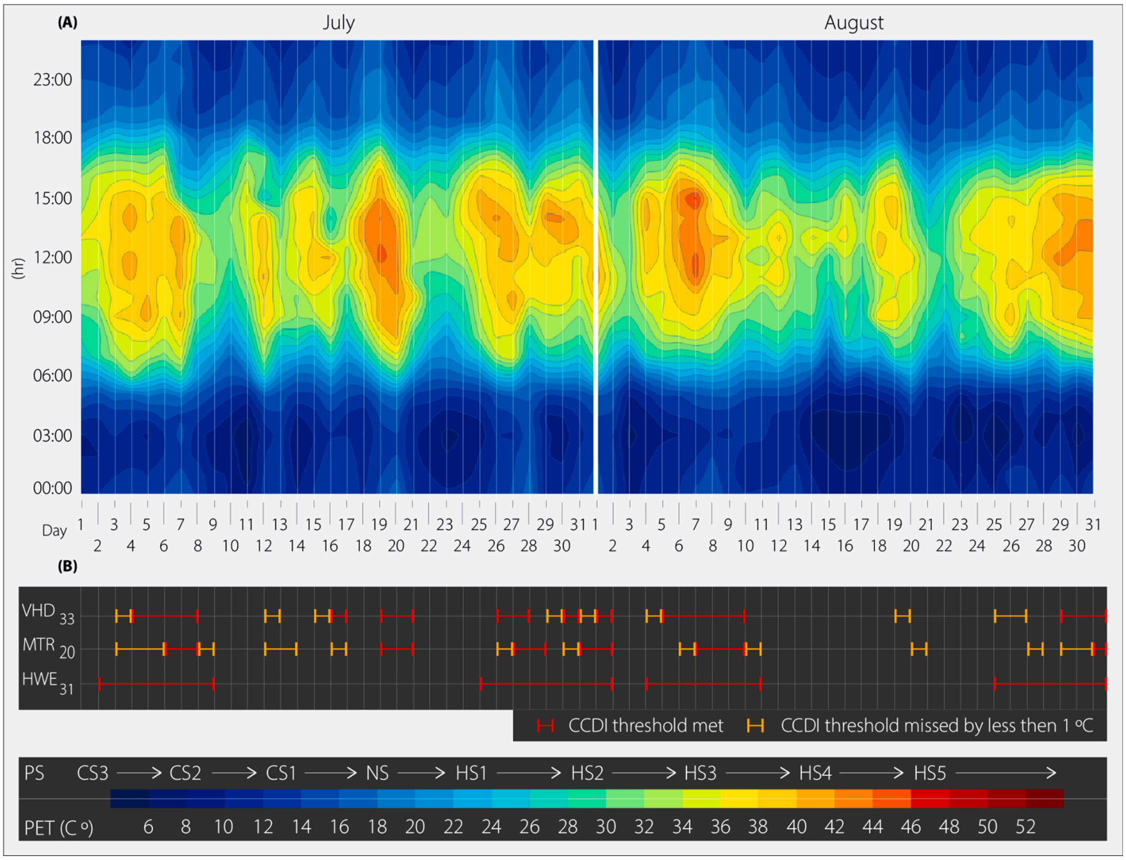

Fig. 6. EBM Heatmap of PET_O values and PS thresholds for the EMS between the months of July and August at a temporal resolution of 1 h against the local EHE definitions for Ankara.

$\overline{Ta_I}$ revealed that $\overline{Ta_I}$ varied between 25.4 °C at 10:00, and 31.9 °C at 17:00. These results were almost identical to those of $\overline{MRT_I}$.

Since indoor speeds remained at 0 m/s, the results in Fig. 5(A) could be directly isolated to the average $\overline{V1.1_O}$ values processed from the AMS. Mean values for both months predominantly remained between 1.0 and 1.5 m/s where speeds tended to drop between the morning hours of 03:00 and 09:00. Finally, when considering the variations of $\overline{RH_O}$ and $\overline{RH_I}$, given the rather steady and moderate $\overline{RH_I}$ levels with averages oscillating between 26.3 and 34.6 %, the oscillations depicted Fig. 5(B), were predominantly a result of the differences with outdoor conditions.

3.2. Outdoor thermophysiological Heatmap and CCDIs

3.2.1. EMS thermophysiological conditions

As demonstrated in Fig. 6(A), the first Heatmap presented the human thermophysiological outputs from the EMS. Although the cooler of the two outdoor stations, it was still possible to identify periods of accentuated stress that could moreover be directly associated to the local EHE definitions. Furthermore, in addition to these specific days, for the cases of VHD_{33} and MRT_{20}, the inclusion of days which just missed such definitions by < 1 °C were also included Fig. 6(B). Nevertheless, given the aggregated temporal window factor associated to the HWE_{31} definition, such a methodology was not applied to this EHE. On days just below the VHD_{33} definition, there was still exposure to at least of HS3 with PET_O values reaching 38 °C for various sequential hours.

On the other hand, days falling within the VHD_{33} threshold presented both: (i) longer periods of incessant HS3, which lasted for numerous days as demonstrated at the beginning/end of each month; and, (ii) susceptibility to intercalated exposure to HS4 with PET values surpassing 44 °C during the early afternoon as particularly identified the 19th – 20th of July, and 6th – 7th of August. On most occasions, both VHD_{33} and MTR_{20} generally took place within a HWE_{31}. Nevertheless, the VHD_{33} during the former illustrated the irrespective vulnerability to HS4, without the requirement for an on-going heatwave.

Finally, regarding to nocturnal patterns with the aid of the correlation to the temporal division of the day as delineated in Eq. (5), N_1 and N_2 presented somewhat similar HS levels, with N_2 presenting a slightly closer proximity to NS conditions, particularly during MTR_{20}. During nocturnal periods, and as a result of the susceptibility to higher diurnal temperatures, the residual peri-urban heat naturally resulted in PS levels remaining in the CS1 range until 23:00 after sunset. Such lingering heat generally lowered within N_1, with PET reaching CS2. Infrequent, yet identified, were the short periods (generally around 03:00) during the two summer months of periods of CS3 within N_1 that proceeded a cooler day.

3.2.2. AMS thermophysiological conditions

In contrast to the EMS, AMS presented greater vulnerability to HS for two interrelated reasons. As shown in Fig. 7(A), it was possible to verify increased exposure to HS during the day, which subsequently relayed to lower CS exposure during the night. Largely, and associated to encompassing UHI dynamics, this implied that in comparison with the EMS, AMS presented a dissimilar continuous pattern of diurnal cycle of direct/latent heat cause-and-effect relationship with the local EHEs. As demonstrated within the AMS's Heatmap, both N_1 and N_2 periods revealed notably lower susceptibility to CS levels, particularly in the case of N_2. During such hours, PS never went below NS with the exception during a few days outside of an EHE after 23:00.

The hours with general HS were within the M and A periods. Such a distribution was similar to the EMS Heatmap in Fig. 6, as were the relationships with the defined EHEs. However, both the general distribution, and degree of the identified HS within such periods were

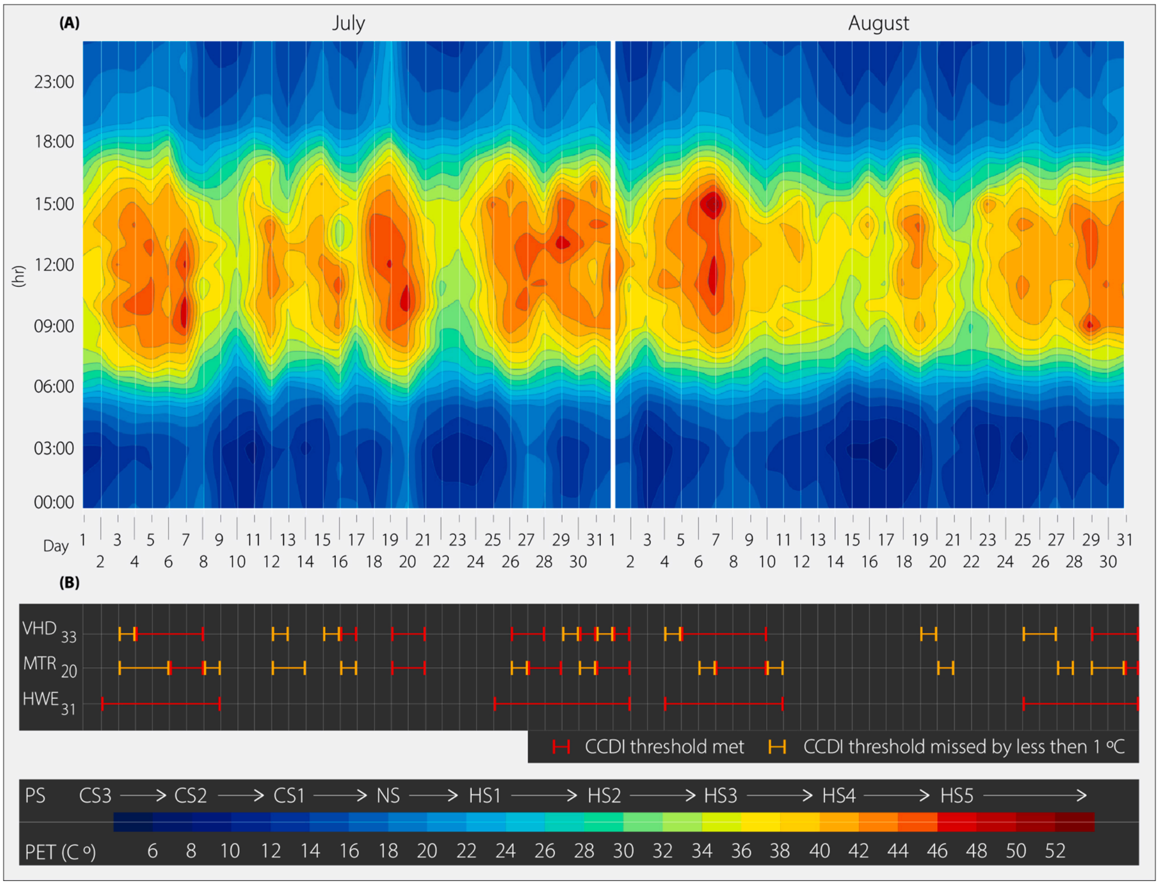

Fig. 7. EBM Heatmap of PET_O values and PS thresholds for the AMS between the months of July and August at a temporal resolution of 1 h against the local EHE definitions for Ankara.

considerably different for the city centre, whereby: (i) during non EHE days (Fig. 7(B)), the frequency of HS3 was noticeably higher particularly during the A period; (ii) very differently to the EMS, during an identified VHD_{33} or HWE_{31}, PET_O values correspondent of a HS4, consecutively remaining above 42 °C; and in addition to the latter, (iii) the occurrence of intermittent peaks of $PET_O > 46$ °C which resulted in a exposure to HS5 levels, with a maximum PET_O value of 50.2 °C on the 7th of August at 15:00.

3.3. *EBM Heatmaps*

3.3.1. *Thermophysiological Heatmap*

At a finer scale of 10 min, Fig. 8(A) demonstrates the Heatmap based upon PET_I variation. It was possible to verify that PS levels constantly remained between HS1 and HS2, with a higher propensity for HS1 during N_1. In cases where a VHD_{33} was observed (Fig. 8(B)), PS tended to remain at HS2 for the entire 24 h, with a small drop around 06:00. During this consecutive period, PET_I varied between 29.0 °C and 32.9 °C, whereby: (i) values ≥ 30 °C mostly took place after 11:00 and successively lasted until at least 23:00; (ii) values ≥ 31 °C occurred between 15:00 and 18:00; and finally, (iii) the limited yet noteworthy occasions of HS3, where PET_I values were ≥ 32 °C on the 7th of July (between 14:50 and 15:00), and the 20th of July (between 16:10 and 18:00).

The disclosed indoor ranges of PS/PET_I results within the EBM Heatmap demonstrated two temporal factors regarding outdoor conditions and EHE thresholds. It was possible to identify a temporal delay in the relationship between: (i) the days in which the heat stress was higher indoors as a result of the EHEs, where the higher identified HS levels were never identified on the same day as the initiation of an encompassing VHD_{33} or HWE_{31}; (ii) the delay (and its subsequent permanence) of outdoor HS during each day and its subsequent transition indoors resultant of the buildings vulnerable construction methods.

3.3.2. *Modified thermophysiological Heatmap*

Within the modified EBM Heatmap as depicted in Fig. 9(A), it was possible to identify significant influences upon PS distribution as a result of the augmentation $V1.1_I$ by 1 m/s. It was important to note that the obtained results were based upon non-temperature alterations, and were instead focused upon the extent of the effects that forced convection through air movement upon human thermoreceptors through the use of the EBM index. The increase of $V1.1_I$ led to an encompassing reduction of PET_I of 3 and 4 K. The impacts of the PET reduction meant that HS levels were both reduced in general, but more crucially, also during periods of PS levels. Within the modified human thermophysiological Heatmap, PS levels were predominantly lower (i.e., between NS and HS1), even during the occurrence of either a VHD_{33} or a HWE_{31} (Fig. 9 (B)).

For July, it was possible to verify that: (i) the impacts of joint EHEs between the 2nd and 8th which witnessed almost incessant PET_I values between ≈ 29 °C and ≈ 30 °C, were reduced to a level of HS1 with resulting PET_I values ranging between ≈ 25 °C and ≈ 26 °C, respectively; (ii) while a HS2 remained on the 20th of July (the second day of a subsequent VHD_{33}), the duration of exposure to such a PS level (originally ranging for a total of almost 21 h) decreased to less than two 2 (i.e., between 16:00 and 17:50); (iii) in the lack any of the EHEs, PS moreover remained either within the NS thresholds, reaching PET_I values as low 21 °C between 06:00 and 09:00, or reached HS1, with a maximum PET_I of 24 °C.

Overall, August revealed a slightly higher exposure to indoor HS,

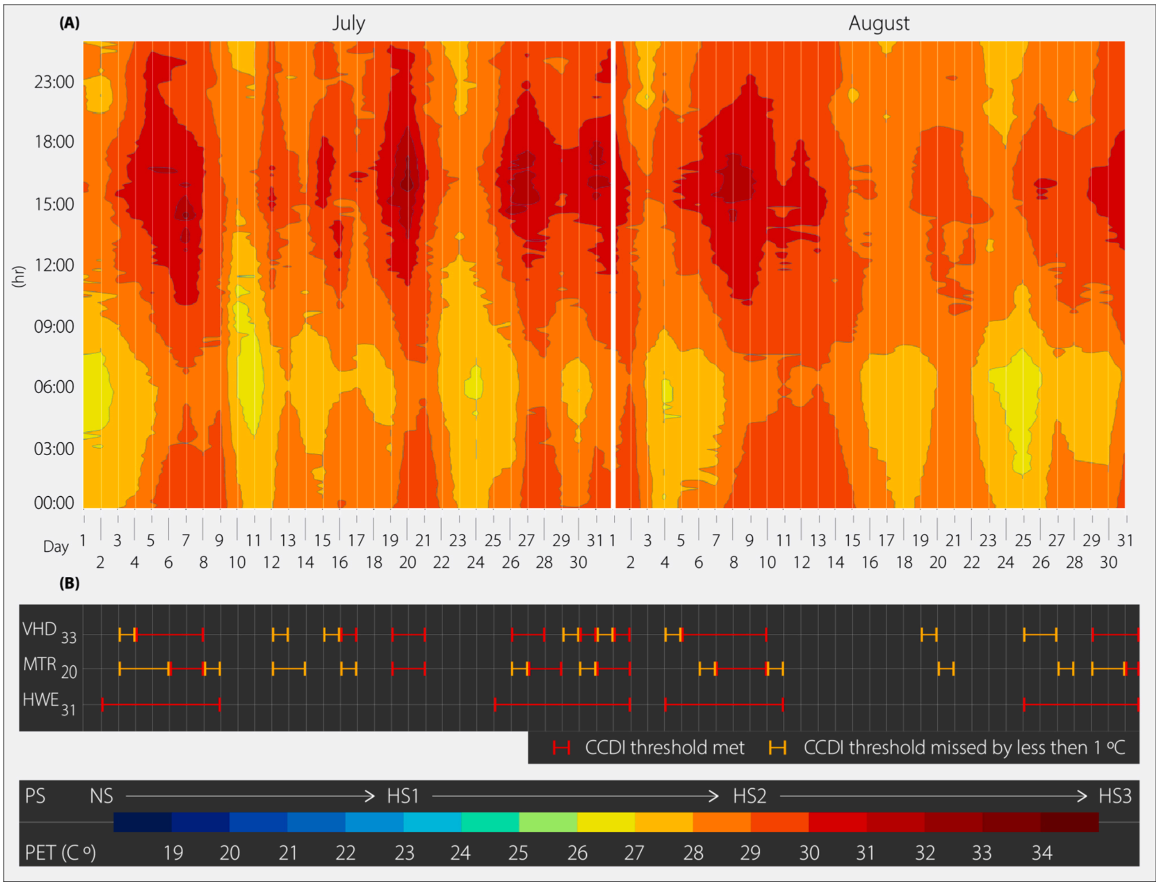

Fig. 8. EBM Heatmap based on of PET_I values and PS thresholds for the KHS between the months of July and August at a temporal resolution of 10 min (A) against the local EHE definitions for Ankara (B).

which can partly be related to a greater frequency of diurnal HS3 within the city centre (outside of any EHEs) between the 9th and the 17th of August Fig. 7(A). The occurrence of higher HS can moreover be associated to the outdoor conditions which took place prior to these days as well. Just before the 9th of August, there was a HWE_{31} of 6 days, which almost joined a preceding HWE_{31}. During this period, although the 2nd and 3rd of the month were below the HWE_{31} definition, given their proximity to the $TX_X \geq 31$°C threshold, a 'technically impartial' HWE_{31} run of 17 days since the 25th of July was recorded. What is more, during this aforementioned temporal window, there were the intercalated additional occurrences of: 9 VHD_{33}, and 7 MTR_{20}. The respective impacts upon indoor conditions for the month of August were subsequently clear, even within the modified thermophysiological EBM Heatmap.

3.4. Cumulative thermophysiological loads

Within the indoor setting, and as to be expected, both immediate and cumulative exposure to HS was different to those found outdoors, such as those presented for the AMS (Appendix B). As portrayed in Fig. 10(A), PETL remained between 3.0°C and 10.0°C for the entirety of July and August, with no periods of thermophysiological 'neutrality'. During both months, and in association to the local EHEs, the identified variation from BC continued to enforce the previously direct/latent cause-and-effect relationship. More specifically, the highest PETL values predominantly took place at the end of a respective VHD_{33}, as exemplified on July the: (i) 7th where values ranged from 7.5 to 9.4 °C between 10:30 and 17:30; and, (ii) 20th where values ranged from 7.5 to 10.0 °C between 10:30 and 21:10.

When considering the $\overline{\text{cPETL}}$ for the original unadulterated indoor human thermophysiological conditions (Fig. 10(B)), numerous conclusions could be extracted, namely: (i) $\overline{\text{AcPETL}}$ constantly presented the highest temperatures in the A period during the two months with pronounced peaks between 8.0 and 8.5 °C; (ii) the second hottest period of the day was revealed to be $\overline{\text{N}_2\text{cPETL}}$, where the N_2 period presented similar average $\overline{\text{cPETL}}$ values to those from the A period; (iii) while similar, $\overline{\text{AcPETL}}$ and $\overline{\text{N}_2\text{cPETL}}$ presented significant punctual differences during periods which combined the occurrence of MTR_{20} and VHD_{33} (irrespective of being within a HWE_{31} window or not) (Fig. 10(C)); and, (iv) the degree of similarity between $\overline{\text{McPETL}}$ and $\overline{\text{N}_1\text{cPETL}}$, even though the M period was exposed considerably higher HS, $\overline{\text{cPETL}}$ remained close to those of the N_1 period.

In the case of the PETL for the altered PET_I as a result of increased of $V1.1_I$, it was possible to determine clear differences as presented in Fig. 11(A), namely where: (i) during July, during a significant part of the day during the EHEs, values generally remained between 0.0 and 3.0 °C; (ii) the periods which still revealed higher PETL values (albeit considerably shorter in duration and lower intensity as first shown in Fig. 10 (A)), took place between the A and N_2 periods at the end of a combined MTR_{20} and VHD_{33} (Fig. 11(C)); and, (iii) during August, particularly

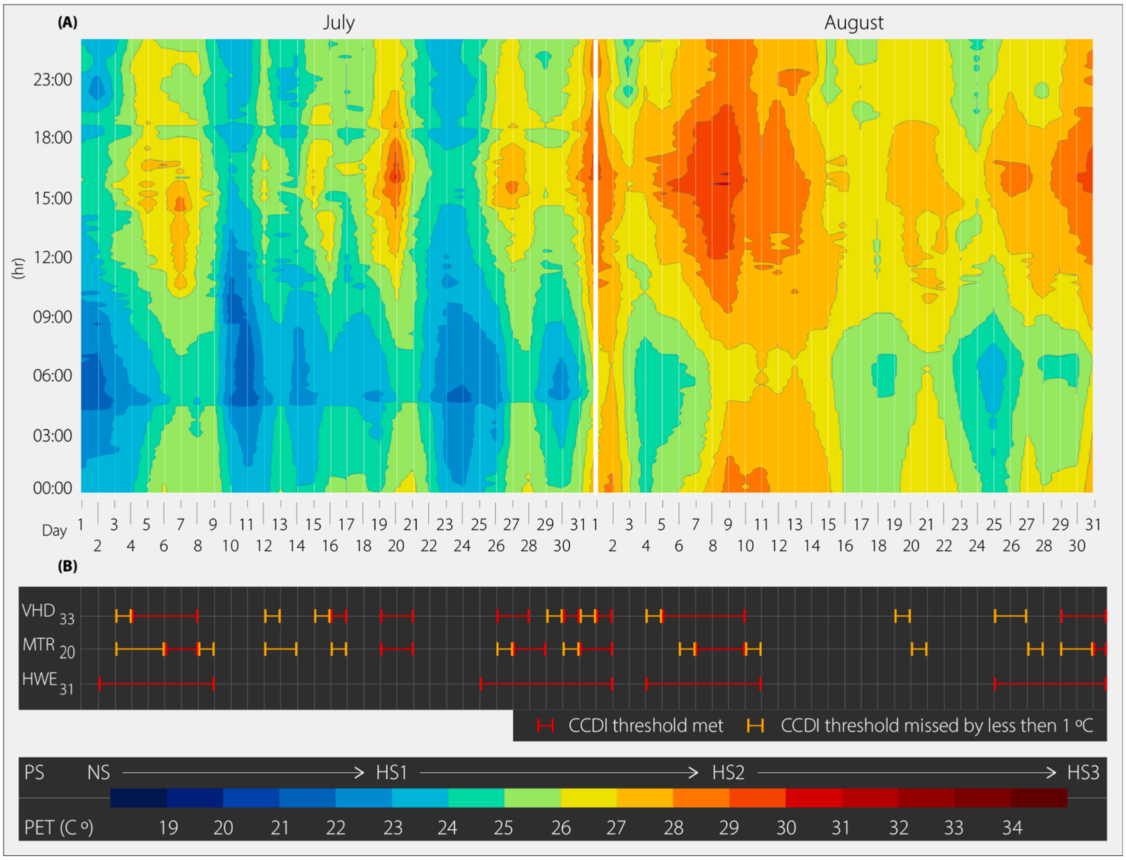

Fig. 9. EBM Heatmap based on of PET_I values and PS thresholds for the KHS between the months of July and August with an augmentation in $V1.1_I$ of 1 m/s at a temporal resolution of 10 min (A) against the local EHE definitions for Ankara (B).

after the EHEs ending on the 10[th], PETL persistently remained between 3.0 and 6.0 °C for almost another week.

With regards to the distribution of $\overline{\text{cPETL}}$ in Fig. 11(B), it was possible to verify both a generally closer approximation to BC conditions, with still a notable increase in trends during the month of August. The explanation for this can be attributed to the fact that while human thermophysiological heat stress levels (both immediate and cumulative) could be reduce via the effects of increased convection upon human thermoreceptors, such reductions were more effective during shorter EHE events. All temporal $\overline{\text{cPETL}}$ periods had the same distribution order, with $\overline{\text{AcPETL}}$ presenting the highest average temporal vulnerabilities, albeit it to a lesser extent during peak periods as exemplified by the 7th / 20th of July, and 9th of August (with respective reductions of $\overline{\text{cPETL}}$ of 3.5 K, 3.2 K, and 1.6 K).

3.5. Bioclimatic comparison with previous summers between stations

The last results of the study enabled the contextualisation of the identified PS vulnerability with previous years in terms of minimum and maximum PET_O values from the EMS and AMS over the past decade for the months of July and August. As shown in Fig. 12, three predominant results were identified, the: (1) clear differentiation in bioclimatic conditions between Ankara's peri-urban and urban contexts during the hottest months of the year; (2) vulnerability to CS4 levels, particularly in the minimum values processed for the EMS, during the hottest months of the year, which as shown in 2012, could take place during the same summer with PS levels surpassing that of HS4/5; (3) regardless of the higher maximum values for the summer 2020 period, overall PET_O averages for the year remained fairly consistent with those processed over the past decade for Ankara.

With regards to the first result, the distinction between bioclimatic conditions amid the two settings could be considerable. This was illustrated by differences in minimum, average, and maximum PET_O values amid the EMS and AMS ranging up to 6.8 K, 7.85 K and 12.3 K, respectively. The second result highlights some vulnerability to CS during the summer months, although this was considerably greater for the case of the EMS as exemplified in 2012, 2015 and 2019. Lastly, and considering the last decade, although with slightly higher HS up to early-August, and lower CS grades for both months, it presented generally typical average summer PET_O values, from both the EMS and AMS ranging mostly between the grades of HS1 and HS2.

4. Discussion

4.1. Indoor human thermophysiological impacts & attenuation

As cities become denser and warmer, means to attenuate human PS has never been as important. In this appreciation, it is crucial to acknowledge that the end receptor of urban bioclimatic stimulus is that of the human biometeorological system. Such an approach is argued to be a foundation in ensuring more environmentally responsive and resilient urban fabrics, of which both indoor and outdoor environments

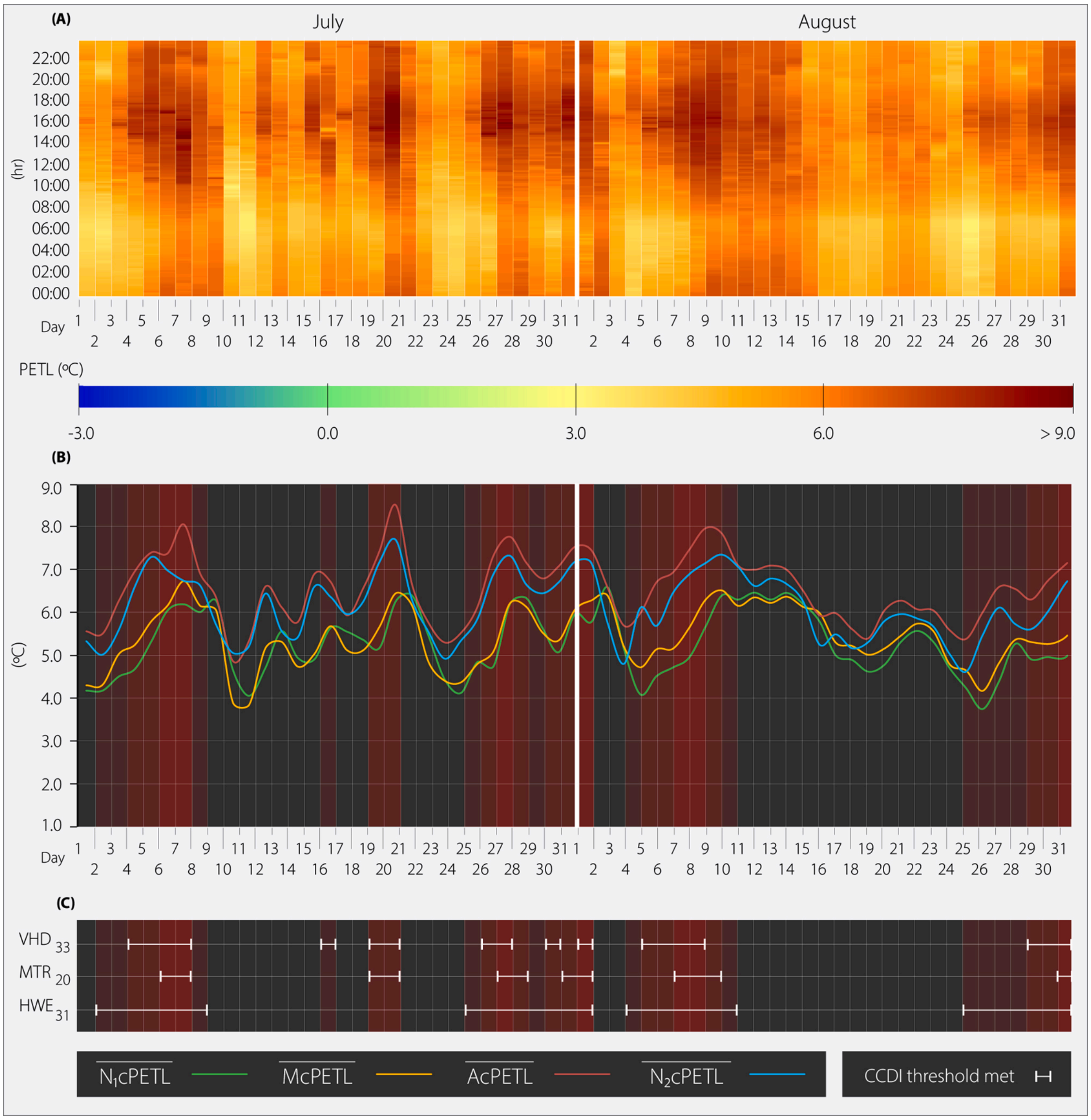

Fig. 10. Distribution of immediate PETL (A) at a 10 min resolution, and defined $\overline{\text{cPETL}}$ periods (6 h) (B) from the original PET_I distribution for July and August 2020 recorded in association with the local EHE definitions for Ankara (C).

play an equally important role in ensuring human well-being and safety standards (Höppe, 2002). While the existing literature has already made substantial progress in addressing heat stress in cities, there is an urgent need for approaches which better integrate outdoor and indoor climatic conditions (Basu & Samet, 2002; White-Newsome et al., 2012).

Correspondingly, there is also the additional need to further develop interdisciplinary 'human-centred approach' methods which better assess, and manage, such indoor/outdoor cause-and-effect risk factors upon the human thermophysiological system (Giannaros et al., 2018; Christen, 2020; Matzarakis, 2020).

The case study of Ankara has been utilised to disclose how such methods can be newly initiated in a city that has witnessed rapid unregulated urbanisation, and significant vulnerability to both existing and future heat events (Yuksel & Yilmaz, 2008). In addition, such susceptibility was yet to be matched with vital local climatic assessment criterion, including initial local EHE definitions (Nouri et al., 2021). The results of the study indicate how such EHEs can aid local/*in-situ* understanding of interconnected indoor and outdoor HS factors, and thus, promote new means to identify, communicate and manage better interdisciplinary response towards urban heat factors.

Within most existing cities, TACs are now a frequent means to lower Ta_I and mitigate excessive HS levels. However this raises two interconnected paradigms. The first, and reverting back to the Urban Energy Balance (UEB) as per Oke (1988), is that the recognised growing propensities of such mitigation requirements in warming cities counterproductively revert back upon the anthropogenic heat flux (e.g., in Santamouris et al. 2001, Dahl 2013, Santamouris 2016, Lundgren-Kownacki et al. 2017, Bouhal et al. 2020). Secondly, TACs moreover, counterproductively, can influence occupants to exceedingly lower Ta_I as a result of influencing thermal diurnal (e.g., in Uno et al. 2003, Rijal et al. 2009, Kim et al. 2017) and nocturnal (e.g., in Imagawa and Rijal 2015, Yang and Olofsson 2017) preferences rather accepting slightly higher temperatures.

As indicated in most recent studies, exemplified by Ebi et al. (2021), the physiological limits of heat tolerance are finite. Moreover, without urgent research and risk management actions, the impending impacts of climate change will continue to augment such HS related hazards, and associated morbidity and mortality (Nazaroff, 2008; Matzarakis, 2022).

Within this research, 'human-centred approach' shed new important perspectives for Ankara. The first was the cause-and-effect relationship

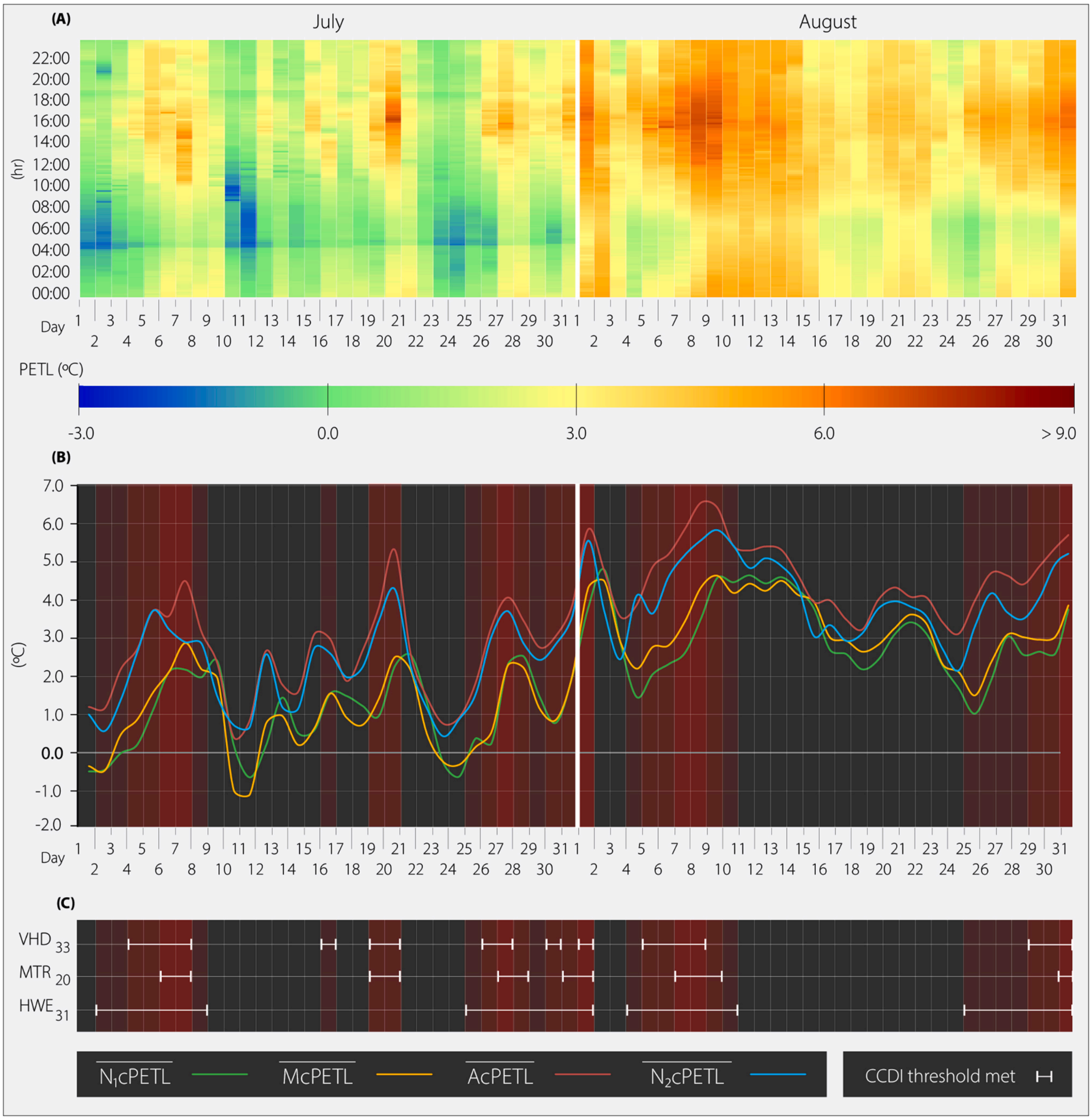

Fig. 11. Distribution of immediate PETL (A) at a 10 min resolution, and defined $\overline{\text{cPETL}}$ periods (6 h) (B) from the altered PET with an augmentation in V1.1$_I$ of 1 m/s distribution for July and August 2020 in association with the local EHE definitions for Ankara (C).

(including that of temporal factors) with newly defined local outdoor EHE thresholds upon both outdoor indoor human thermophysiological thresholds within vulnerable out-dated residential construction methods whereby:

- Even during non EHE, PET$_I$ values did not drop below 27 °C. However, in the occurrence of a VHD$_{33}$, PS levels remained at HS2 for almost 24-hous which PET$_I$ varying between 29.0 and 32.9 °C.
- Ranges of PET$_I$ demonstrated two temporal factors pertaining to the direct/latent heat cause-and-effect correlations with EHEs, these being the temporal delay in: (1) the days in which the HS was higher indoors as a result of the EHEs, where the upper HS levels were never identified on the same day as the initiation of an VHD$_{33}$, nor of a HWE$_{31}$; and also, (2) the (and subsequent permanence) of outdoor HS during each day and its subsequent transition delay (frequently in the range of ≈ 4 h) to the indoors.
- Excess PET$_I$ loads demonstrated that PETL remained between 3.0 and 10.0 °C for the entire two months, with no periods of thermophysiological 'neutrality'. In association to the local EHEs, PETL followed the same oscillation patterns from the aforementioned direct/latent heat cause-and-effect dynamics between indoors and outdoors.
- $\overline{\text{AcPETL}}$ constantly presented higher exposure to HS during the two months with peaks varying between 8.0 °C and 8.5 °C. The second hottest period of the day was $\overline{\text{N}_2\text{cPETL}}$, where the N$_2$ period presented similar average $\overline{\text{cPETL}}$ values. Irrespective of this similarity, $\overline{\text{AcPETL}}$ and $\overline{\text{N}_2\text{cPETL}}$ illustrated significant punctual differences during days which witnessed the occurrence of MTR$_{20}$ and VHD$_{33}$. Regardless of being within a HWE$_{31}$ window or not.

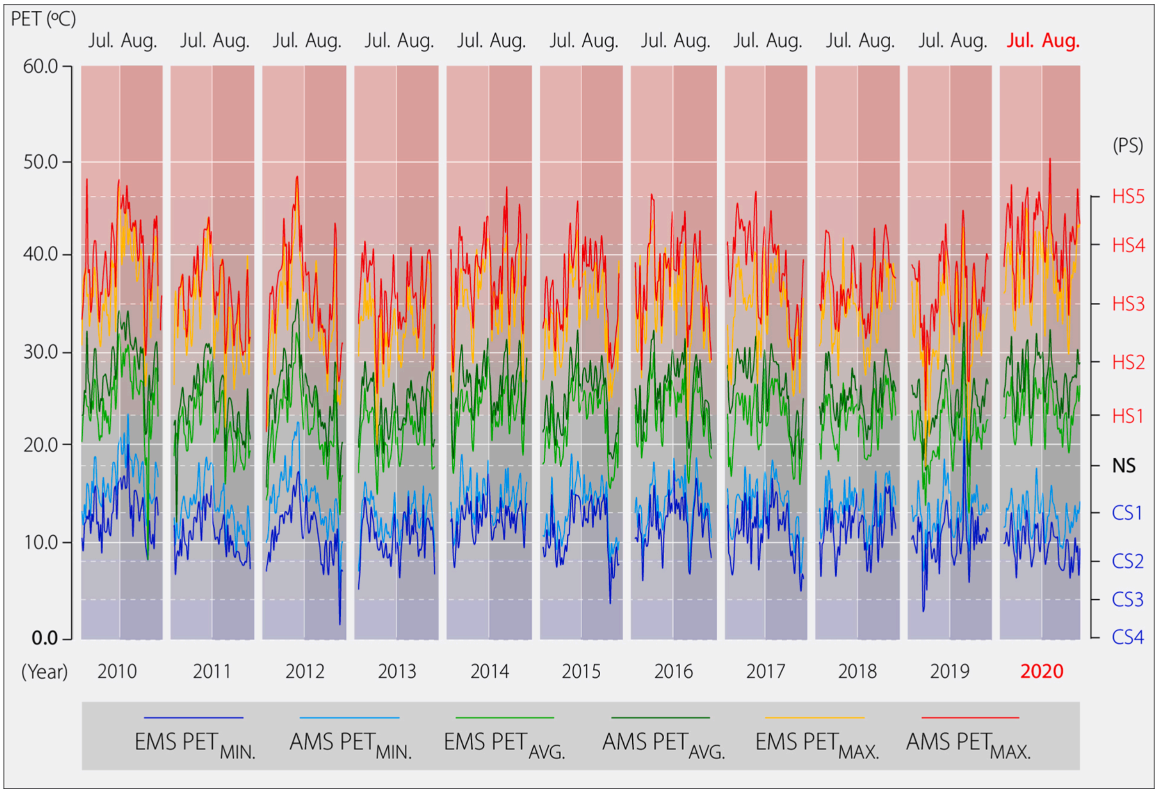

Fig. 12. Daily distribution of Min., Avg., and Max. PET_O values for July and August over the past decade for the EMS and AMS.

- There was a stronger than expected similarity between indoor $\overline{\text{McPETL}}$ and $\overline{\text{N}_1\text{cPETL}}$, even though the M period was exposed to hours with considerably higher HS (i.e., between the hours of 10:00 and 12:00). Such an occurrence can however be directly related latent heat cause-and-effect processes within the indoor context.

The second factor was the quantifiable and measurable influences upon indoor thermal conditions as a result of the augmented convection through the increase of $V1.1_I$, and its direct/measurable reductions upon PET_I values (be them immediate or cumulative over different predetermined periods of the day) whereby:

- General reductions of ≈ 3–4 K in PET_I were observed without the need for TACs, including during EHEs where original values were reduced to a level of HS1 with resulting lower PET_I values ranging between ≈ 25 °C and ≈ 26 °C. Although there were still some periods of the day witnessing HS2, its duration was considerably lower, i.e., decreasing to 2 h from the original 21 h.
- PETL with an increase of $V1.1_I$ demonstrated that on days witnessing an EHE, values were considerably lower and generally ranged between 0.0 and 3.0 °C. It was also revealed that at the end of a combined MTR_{20} and VHD_{33}, the time of day with slightly higher PETL were during the A and N_2 periods. In the case of a long HWE_{31}, as was seen in August, PETL presented higher values after this event, where it persistently remained between 3.0 and 6.0 °C for almost another subsequent week
- Through the distribution of $\overline{\text{cPETL}}$ trends for the different assessments periods via the increase of 1.0 m/s in $V1.1_I$, a generally closer approximation to BC conditions was identified. However, in comparison to July, $\overline{\text{cPETL}}$ remained higher during the month of August. The reason for this can be credited to the fact that while human thermophysiological HS levels (both immediate and cumulative) could be reduced via the effects of increased convection upon human thermoreceptors, such reductions were more effective during shorter EHE events.

4.2. Study limitations

4.2.1. Integration with qualitative thermal adaptive processes

Within the existing literature, approaches to thermal comfort assessments can be predominantly broken into two groups, those that focus upon quantitative aspects and others which focus upon qualitative aspects. In a review study conducted by Nouri and Costa (2017b) it is was highlighted that humans perceive the environment differently, and psycho-sociological factors have a significant influence upon the thermal perception of their surroundings. Thus far, this has been well reflected within international scientific community, including in its continued efforts to link qualitative adaptive processes with means to enhance the 'availability of climatic choice' (e.g., Givoni, 1976; Nikolopoulou et al., 2001; Givoni et al., 2003; Nikolopoulou & Steemers, 2003; Thorsson et al., 2004; Katzschner, 2006; Gomez-Azpeitia et al., 2011; Chen & Ng, 2012; Nouri & Costa, 2017a).

The methodology undertaken in this research has focused upon the first type of thermal comfort assessment, i.e., quantitative. That being said, while it focuses upon the physiological attributes of urban HS vulnerability, it raises opportunities for further study that can combine methods to identify thermal adaptive processes in the indoor environments as suggested by Nicol and Humphreys (1973) and de-Dear and

Brager (1998). More concretely, while the different quantitative Heatmaps present oscillations human PS thresholds based upon and EBM index, this does not imply that everyone shall perceive the identified HS in the same way. Nor does it mean that the convective cooling results will satisfy everyone in the same manner.

Nevertheless, the novelty of this study in relating EBM results between indoor and outdoor conditions against local EHEs depicts upon the assessment of an indoor '*objective component*' (de-Dear et al., 2016), where all individuals shall undertake their own subjective evaluation (Höppe, 2002; Liu et al., 2020). Of course, to properly assess qualitative evaluations of the conditions assessed in this study, test subjects and interviews would be required. While the aims of this study support such further research, it goes beyond its current scope.

It is important to recognise that the reversal of the aforementioned relationship between qualitative and quantitative thermal comfort methodologies is also valid. In other words, when working towards constructing local HS assessments within cases such as Ankara, universal criteria and/or assessment must be first established based upon human anatomy. Such criterion is be based upon uniform criterion that are common to the human biometeorological system, one which is carefully detailed in the aforementioned MEMI methodology pioneered in the '*Die Energiebilanz des Menschen*' as disseminated by Höppe (1984).

This being said, the results of the study reveal noteworthy associations between its quantitative EBM outcomes, and those of qualitative nature in existing literature pertinent to the psycho-social extensions of the 'thermally acceptable range'. More specifically, expansions of such acceptability ranges of Ta_I as determined (e.g., in ASHRAE 2017, He et al. 2020) matched those retrieved by this research given the reduction of between ≈ 3 - 4 K in PET_I, with an equal increase of $V1.1_I$ by 1.0 m/s. These obtained reductions resulted in PET_I values led to reductions in PS levels during critical HS periods indoors through forced convective cooling, rather than temperature induced cooling through more energy consuming domestic TACs.

Through the application of the PET index (and its applied derivatives), in alignment with the ensuing approach of Höppe (1999), it was feasible to counteract the lack of human biometeorological sensors that otherwise enable the perception of individual climatic parameters (including Ta). Pertaining to the approach of indoor HS, this study conducted one of the first approaches to this thermal risk factor through the use of the PET index (both immediate and cumulative), with the further intention of exploring how modifying initial input parameters can influence overall thermophysiological exposure to HS. Following this line of reasoning, such an alteration could not be undertaken using an ICDN based upon only Ta_I, as elaborated by Nouri et al. (2021). Although focused upon a KGC '*Csa*' within the Mediterranean case of Barcelona, and although specific to outdoor conditions, the research conducted by Algeciras and Matzarakis (2015) also serves as one of the very few other studies that (in addition to MRT_O), also altered investigated the effects of augmenting $V1.1_I$ by 1.0 m/s to reduce PET_O (and their associated PS thresholds) within the urban public realm.

The application of the EBM approach in comparison with its Ta_I based predecessor can moreover be interlaced with the consensus as highlighted by Arens et al. (2010). More precisely, while indoor thermal comfort can indeed be effectively investigated based upon Ta_I alone, this is based upon the particular condition that such a context has still-air conditions, moderate humidity, and with limited exposure to significant radiation fluxes. The origins of this line of reasoning extends back to the comprehensive correlations made for a reference indoor climate as determined by Höppe (1999) relative to the calculation methodology of the PET index, namely where: (i) $MRT_I = Ta_I$; (ii) $V1.1_I = 0.1$ m/s; and (iii) $RH_I = 50\%$ when $Ta_I = 20$ °C. Evidently, such stable and specific interior conditions are scarce, and while the Ta_I based ICDN could be undertaken within such conditions as determined by the interior KHS measurements, it certainly marked a far less applicative and replicable capacity in comparison to the EBM approach.

4.2.2. Approaches towards different seasons and cold stress

Ankara is a city that is vulnerable to both CS and HS extremes given its KGC. Previous studies have already identified its vulnerability towards CS (Türkoğlu et al., 2012; Çalışkan & Türkoğlu, 2014; Nouri et al., 2021). However, within the existing literature there is no known study that has undertaken an analysis between indoor and outdoor CS using an EBM index, nor with Ta. Given the scope and length of this study that was centred upon the summer, this assessment was not undertaken in this research either. Naturally, this limited the study from determining how the vulnerable construction typologies interact with CS exposure during the winter. Furthermore, the results of this study also highlighted the opportunity to further investigate CS for the summer period given the revealed bioclimatic differences between the city centre and its peri-urban surroundings. A further study focusing upon nocturnal variations between the EMS and AMS would generate further understanding into UHI patterns (e.g., Oke et al., 1991; Alcoforado & Andrade, 2006), nocturnal ventilation (e.g., Santamouris et al. 2010; Solgi et al., 2018), and EHEs (e.g., Giridharan et al., 2005; Beckmann et al., 2021).

4.3. Urban heat and perspectives for further study

Considering the results obtained for this study, managing thermophysiological risk factors within cities such as Ankara can be approached in two ways, namely via:

- Shorter-term processes which include the establishment/solidification of means to establish methods to cope with human PS, including the disclosed local specific EHEs, and their subsequent implementation towards heat-warning systems.
- Longer-term process of implementing adaptation measures (be them indoor or outdoor orientated) to improve the encompassing thermal resilience of urban realm as a whole.

Neither is more important than the other. On the contrary, the imperative key to managing PS in Ankara is combing both processes within encompassing urban bioclimatic planning guidelines that shall aid both its expansion, but moreover, consolidate the thermal resilience of its existing and expanding fabric. In this way EHEs can be better managed and subsequently attenuate heat related risk factors during specific times of the month and times of day.

It is moreover argued that it shall be comparatively convoluted to focus only on addressing a large amount of thermally vulnerable residential dwellings, whose shells require updating to comply with building codes. Further exploration is needed, including but not limited to the to the local introduction of the consolidating, yet already promising, know-how phase change and reflective materials around/within building shells, which can further improve the performance of the respective shell to such HS vulnerabilities (Doulos et al., 2004; Santamouris et al., 2011; Shi & Zhang, 2011; Santamouris, 2014; Nematchoua et al., 2020). Moreover, complementing *in-situ* solutions including the better implementation/understanding of shading systems (Stazi et al., 2014), integration with adjacent urban vegetation (Nouri et al., 2018; Taleghani et al., 2019), misting systems (Alvarez et al., 1991; Ishii et al., 2009), and intrinsic relationship with adjacent urban morphological characteristics in terms of radiation susceptibility (Herrmann & Matzarakis, 2012; Nouri et al., 2017; Tong et al., 2017) can also make valuable contributions to such efforts.

These endeavours, although inarguably essential, need to be accompanied with processes whose results shall be palpable in the shorter term. To be more specific, while such timely physical adaptations would be taking place, this could be integrated within heat action plans that incorporate early warning and response systems to alert of impending EHEs (Constantinescu et al., 2016; Matzarakis, 2016; Hes et al., 2018). Invariably such plans are even more quintessential given the noxious combination of the discussed vulnerable residential dwellings, and moreover, the more vulnerable members of the public that live within them (Afacan & Demirkan, 2016; Rosenfelder et al., 2016; Ebi et al., 2021; Matzarakis, 2022).

Naturally, such longer-term processes supersede the scope of this study. Nevertheless, based upon the outputs of the study, some synoptic orientations into further research opportunities can certainly be suggested, namely:

- Concomitant to the approach as disseminated by Matzarakis (2020), one must contemplate upon the 'positive factors' in addressing urban atmospheric factors, including indoor/outdoor thermal comfort vulnerabilities. As identified in this study, between PET_O and PET_I, there were clear: (i) temporal delays in peak HS during the day (of ≈ 4 h); and (ii) delays for EHE effects to be felt indoors, whereby the highest PS thresholds were either identified in the last day of an event, or remain high after a particularly culmination of outdoor HS aggravations. Such direct/latent heat cause-and-effect relationship with newly defined local extreme heat thresholds can certainly be a starting point to clue decision makers into establishing even the most primitive (yet useful) warning system.
- Given the CCDI evaluations in Nouri et al. (2021) since 2008, and the PET_O evaluations over the past decade in this study, the hot-dry summer of 2020 can overall be considered a slightly-above average year for HS. This implies that both the EHEs and general human thermophysiological conditions, even for present conditions, can be easily exceeded. For this reason, and considering the higher temperatures for 2021 that resulted in record breaking fires in Turkey, the research by Ertuğrul et al. (2021) shall remain as symbiotic reminder of the urgent need to accelerate the pace to address ever present vulnerabilities, including for Turkish urban centres.

5. Concluding remarks

The outputs from this research, based upon the case Ankara, illustrate its growing susceptibility to local extreme heat events, and moreover upon the direct/latent heat cause-and-effect connections with heat stress during a typical summer period within vulnerable, yet typical, residential indoor dwellings. Retrospectively, three key summative remarks can thus be distinguished:

1 There needs to be a fortification in means to approach indoor heat stress risk factors through 'human-centred approaches' – where human biometeorological approaches are better associated to indoor/outdoor conditions and their cause-and-effect dynamics upon humans - without the over-dependence on solely counterintuitive air conditioning practices. As to be expected, outdoor temperatures were a lot higher in such conditions, with a maximum value reaching 50.2 °C on the 7th of August from the city station. However, as a result of the forced convective cooling by increasing indoor airspeed (by 1.0 m/s), indoor temperatures during such heat events were proved to be reduced between ≈ 3 and 4 K. Such results directly support the interrelated numerical outputs from more qualitative evaluations of thermal comfort studies, focused upon the expansion of 'thermal acceptability ranges' (of ≈ 3 °C in indoor air temperature) as an outcome of similar indoor convective cooling processes through similar/identical air speeds.

2 While the outcomes are specific for the case of Ankara, the more encompassing perspectives however universally call for the interdisciplinary 'bridging' with urban decision makers and designers in finding means to address increasing indoor/outdoor heat stress vulnerability in densifying cities – both through wholesomely interconnected short-term and long-term processes through urban bioclimatic management. More specifically, examples of the short-term fall upon utilising the local extreme heat event definitions for Ankara, and learning from international patterns and/or guides. This includes the steps towards the opportunity to alert the members of the public (including its more vulnerable members of the public, either due to their health conditions, and/or, their living conditions). These altert mechanisms can be commenced through initial steps in establishing both local heat warning systems, and symbiotically, with better bioclimatic mapping of the disclosed vulnerabilities. As this consolidates, efforts requiring more time can also be physically initiated within the actual urban fabric to improve its overall thermal responsiveness as a whole. This bottom-up approach will be one that shall take advantage of local *in-situ* characteristics, and their associated risk factors to propose different typologies of thermal sensitive architectural and urban design measures through interdisciplinary bioclimatic planning.

3 To conclude on a future perspective, as stated in this study, the physiological limits of local heat tolerance are finite. Yet Ankara serves as a stereotypical example of a continually densifying city, with the common oversight into what implications this is already having upon existing heat stress levels, and more importantly, the increase of these levels in an era of further climate change.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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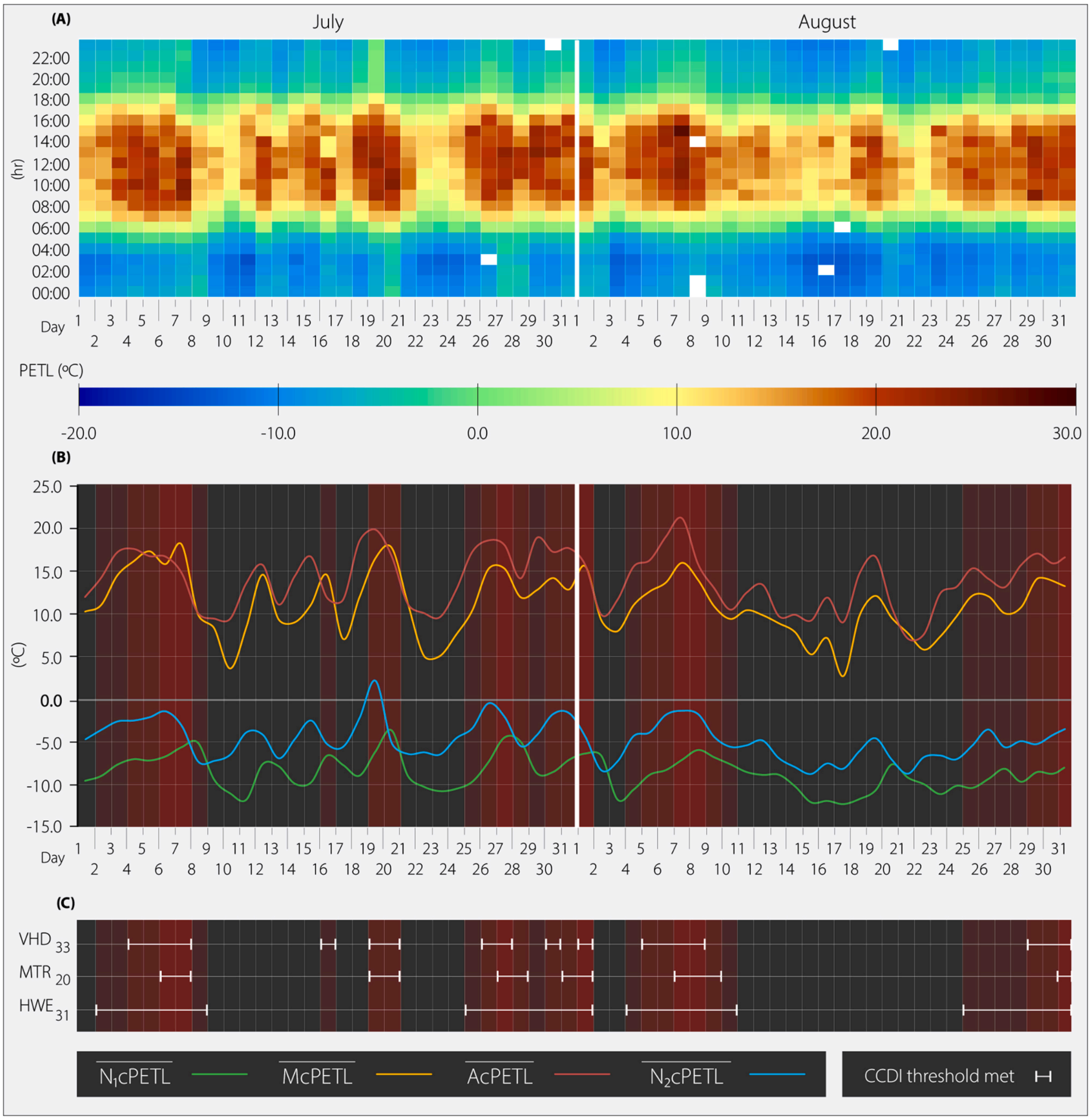
Appendices

Appendix A
Summary of Ta_O based core CCDIs to define local EHEs for Ankara as applied in Nouri et al. (2021).

Group	CCDI	Designation	Unit
(A)	TX_X	Max Ta_{Max}	(°C)
	TN_X	Max Ta_{Min}	(°C)
	TX_N	Min Ta_{Max}	(°C)
(B)	TX_M	Mean Ta_{Max}	(°C)
	TN_M	Mean Ta_{Min}	(°C)
(C)	TX_{10p}	Cool Days	(%)
	TX_{90p}	Warm Days	(%)
(D)	TN_{10p}	Cool Nights	(%)
	TN_{90p}	Warm Nights	(%)
(E)	MTR_{20}	Monthly Tropical Night	(# Days)
	VHD_{33}	Very Hot Day	(# Days)
	HWE_{31}	Heat Wave Event	(# Evts.)
(F)	WSDI	Warm Spell Duration Index	(# Evts.)
	SU_{25}	Annual Summer Days	(# Days)
	TR_{20}	Annual Tropical Nights	(# Days)



Appendix B. Distribution of immediate PETL (A) at a 1 hour resolution, and defined $\overline{\text{cPETL}}$ periods (6 h) (B) from the PET_O for July and August 2020 processed from the AMS, in association with the local EHE definitions for Ankara (C).

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