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RESEARCH

Detection and quantification of seasonal human heat and cold stress frequencies in representative existing and future urban canyons: the case of Ankara

A. Santos Nouri[1] · I. Charalampopoulos[2] · Y. Afacan[1] · A. Matzarakis[3,4]

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Abstract

Based upon a 'human-centred approach', combinations of existing and new methodologies were applied to determine how Ankara's morphological characteristics influenced the magnitude/frequency of Cold Stress (CS) and Heat Stress (HS) to detect/quantify seasonal and yearly human thermal stress frequency. To quantify these conditions upon the human biometeorological system, the Physiologically Equivalent Temperature (PET) was utilised by processing climatic variables from Ankara's Meteorological Station (AMS). In situ assessments of human thermophysiological thresholds were undertaken within characteristic existing/future Urban Canyon Cases (UCCs), with a further stipulation of three interior Reference Points (RPs). Indoor PET values were moreover calculated within a stereotypical vulnerable residential dwelling. Seasonal frequencies revealed that winter PET values frequently ranged between 0.0 and − 19.9 °C, with corresponding summer values frequently ranging between 35.1 and 46.0 °C. Accounting for Ankara's urban morphology, yearly frequency of No Thermal Stress remained at ~ 48%, CS remained at ~ 26%, and HS ~ 28%. HS varied the most between the eight evaluated Aspect Ratios (ARs). It reduced by up to 7.1% (114 min) within the Centre (RP_C) area of UCCs with an orientation of 90°. Out of twelve orientations, the highest HS frequency took place between 105 and 135°. Including in $UCC_{3.50}$, the frequency of HS almost always remained above 72% (2592 min).

Highlights

- Urban cold/heat stress evaluated within diverse urban morphological in situ settings.
- Present/future urban canyons studied to define thermophysiological stress frequency.
- Physiologically Equivalent Temperature used to assess thermal stress on human body.
- New methodical approach to identify local seasonal and yearly thermal stress frequency.

✉ A. Santos Nouri
andre.nouri@bilkent.edu.tr

I. Charalampopoulos
icharalamp@aua.gr

A. Matzarakis
andreas.matzarakis@dwd.de

[1] Department of Interior Architecture and Environmental Design, Faculty of Art, Design and Architecture, Bilkent University, 06800 Bilkent, Turkey

[2] Laboratory of General and Agricultural Meteorology, Agricultural University of Athens, 118 55 Athens, Greece

[3] Research Centre Human Biometeorology, German Meteorological Service, 79104 Freiburg, Germany

[4] Faculty of Environment and Natural Resources, Albert-Ludwigs-University, 79085 Freiburg, Germany

Abbreviations

'*BSk*'	Cold semi-arid climate according Köppen-Geiger Classification (-)
'*Csa*'	Warm temperate with dry hot summer according Köppen-Geiger Classification (-)
'*Dsa*'	Snow/cold climate with dry/hot summer according Köppen-Geiger Classification (-)
'*Dsb*'	Snow/cold climate with dry/warm summer according Köppen-Geiger Classification (-)
AR	Aspect ratio (-)
DP_1	Diurnal period 1 (i.e. between 09:00 and 17:00) (-)
DP_2	Diurnal period 2 (i.e. between 12:00 and 15:00) (-)
mPET	Modified physiologically equivalent temperature (°C)
MRT_I	Indoor mean radiant temperature (°C)
MRT_O	Outdoor mean radiant temperature (°C)
Oct	Cloud cover (1/8)
OR	Orientation (°)
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 (%)
$RP_\#$	Reference Point (-)
SVF	Sky View Factor (0/1)
Ta	Air temperature (°C)
Ta_I	Indoor air temperature (°C)
Ta_O	Outdoor air temperature (°C)
Tg_I	Indoor globe temperature (°C)
U-Value	Thermal Resistance (W/m^2k)
$UCC_\#$	Urban Canyon Case (-)
$V1.1_I$	Indoor air speed at 1.1 m (m/s)
$V1.1_O$	Outdoor wind speed at 1.1 m (m/s)
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)
H/W	Height-width-ratio (-)

Acronyms

AMS	Ankara's Meteorological Station
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
CCDI	Climate Change Detection Indices
C	Central (Pertaining to RP)
CS#	Cold Stress #
CTIS	Climate-Tourism/Transfer-Information-Scheme
EBM	Energy Based Model
EHEs	Extreme Heat Events
FDD	Frequency Distribution Diagram
GCM	Global Circulation Model
HS#	Heat Stress #
ICDN	Indoor Cooling Degree Necessity
IPCC	Intergovernmental Panel on Climate Change
KGC	Köppen-Geiger Classification
KHS	Kestrel Heat Stress
LL	Left Lateral (Pertaining to RP)
MEMI	Munich Energy-balance Model for Individuals
MS	Meteorological Station
NTS	No Thermal Stress
NTS_{EXP}	No Thermal Stress Expanded
RCM	Regional Climate Model
RCP	Representative Concentration Pathways
RL	Right Lateral (Pertaining to RP)
SDG	Sustainable Development Goal
PS	Physiological Stress
TÜBİTAK	Scientific and Technological Research Council of Türkiye
WMO	World Meteorological Organisation

1 Introduction

This research was focused upon a 'human-centred approach' that relays to the aim of determining and quantifying environmental impacts upon the human thermophysiological system within Ankara's urban centre. Such a perspective is one which is conducive with the "human biometeorological evaluation of the atmospheric environment" and "to clarify whether or not planning instruments are available for maintaining and improving the human biometeorological situation." (Matzarakis et al. 2007, p.1). The disclosed rational can directly be associated with the early interdisciplinary growing necessity to ensure thermal responsive local urban environments (Hebbert and Mackillop 2013; Reiter and Herde 2003; Wilbanks and Kates 1999). For this reason, while the use of Global Circulation Models (GCMs) and Regional Climate Models (RCMs) remains paramount to approach more encompassing climate system dynamics, an equal weight must be attributed to local scale impacts, and just as importantly, their impact upon humans (Matzarakis 2021; Nouri 2013; Nouri et al. 2021). Such an approach can be directly associated to the exploration of adaptive measures that are also defined upon local urban characteristics (Matos Silva 2016; Nouri and Costa 2017b). In association, and in connotation with the climate change adaptation agenda between scales, this approach addresses the "…long-term human health or social and environmental effects of inaction as well as the possibility to piggy-back climate change into more urgent local agendas such as improved local environments and liveability of cities…" (Corfee-Morlot et al. 2009, p.3). These solidifying local agendas have numerous cyclic socio-economic benefits in an era of climate change, including those related to wholesome sustainable tourism practices and familiarity (Lopes et al. 2021, 2022; Matzarakis et al. 2010b).

The 'human-centred approach', moreover, entails a supplementary modification to environmental risk quantification with regard to human thermophysiological exposure within divergent interrelated scales and urban indoor/outdoor settings. Depicting upon the interrelation of analytical scale, the earlier studies (e.g. Gasparrini et al. 2015; Hebbert and Webb 2007) indicated that scientific understanding of environmental 'hazards' remained frequently upon exposure to those of huge impact, but low frequency; on the other hand, less was known about the high frequency microclimatic exposure within consolidated urban fabrics. While such a rationale can be 15 years old, the scientific community continues, today, to work towards the better identification of means to identify and quantify impacts upon the human biometeorological system, including within encompassing review articles (Charalampopoulos 2019; Charalampopoulos and Nouri 2019; Coccolo et al. 2016; Nouri et al. 2018a; Potchter et al. 2018, 2022; Staiger et al. 2019). These efforts reiterate early acknowledgments that cities hold an infinite number of microclimates, and distinguishing the different microclimates amid its urban fabric and structures becomes just as paramount (Burt et al. 1982; Matzarakis et al. 1999; Mayer and Höppe 1987). For this reason, such environmental management can fully exploit this symbiotic relationship by locally exploring built environment characteristics, including, but not limited to, urban morphological dimensions, vegetation, topography, and surface materials (Doulos et al. 2004; Fröhlich and Matzarakis 2015; Herrmann and Matzarakis 2012; Nouri et al. 2018a, 2017; Thorsson et al. 2017).

As described by the existing literature, and as synoptically summarised in Fig. 1, the human physiological system responds to environmental Heat Stress (HS) stimulus through two predominant mechanisms, through the reallocation of blood distribution towards the skin (i.e. via vasodilation) to improve the efficacy of heat transfer from muscles to the skin and subsequently to the encircling environment, and through the secretion of sweat onto the skin which evaporates and resultantly attenuates body heat (Ebi et al. 2021; Kenny and Jay 2013).

Such core human biometeorological principals have already been incorporated within thermal comfort models, including the Munich energy-balance Model for Individuals (MEMI) (Höppe 1984, 1993). Still within HS conditions, the redistribution of blood flow resulting in peripheral vasodilation moreover causes cardiac demand that increases the beat rate, while in addition, decreasing the heart's filling pressure (Crandall and González-Alonso 2010; González-Alonso 2012). For these reasons, elevated cardiovascular pressure is a main point of concern during heat extremes due to the fact that older age groups die more from cardiovascular events in comparison to almost all other heat-related causes of death (Bunker et al. 2016). This being said, HS moreover presents a risk for all age groups, including factors associated to dehydration, which can lead to strain and damage (in excess) upon muscle groups and other vital organs of the body (Dematte et al. 1998; Ebi et al. 2021; Roncal-Jimenez et al. 2015; White 2006). In association, and further emphasising the vulnerability even in the most athletic groups and settings, recent studies have moreover called upon the crucial significance of heat stress management within Olympic Games events (Matzarakis et al. 2018a, 2019).

In comparison to HS risks, the impacts of CS extremes on the human body have been less studied in relationship to urban cold spells (Barnett et al. 2012; Chen et al. 2019). One of the reasons for this is that while cold spells can also significantly increase mortality, in comparison to heat

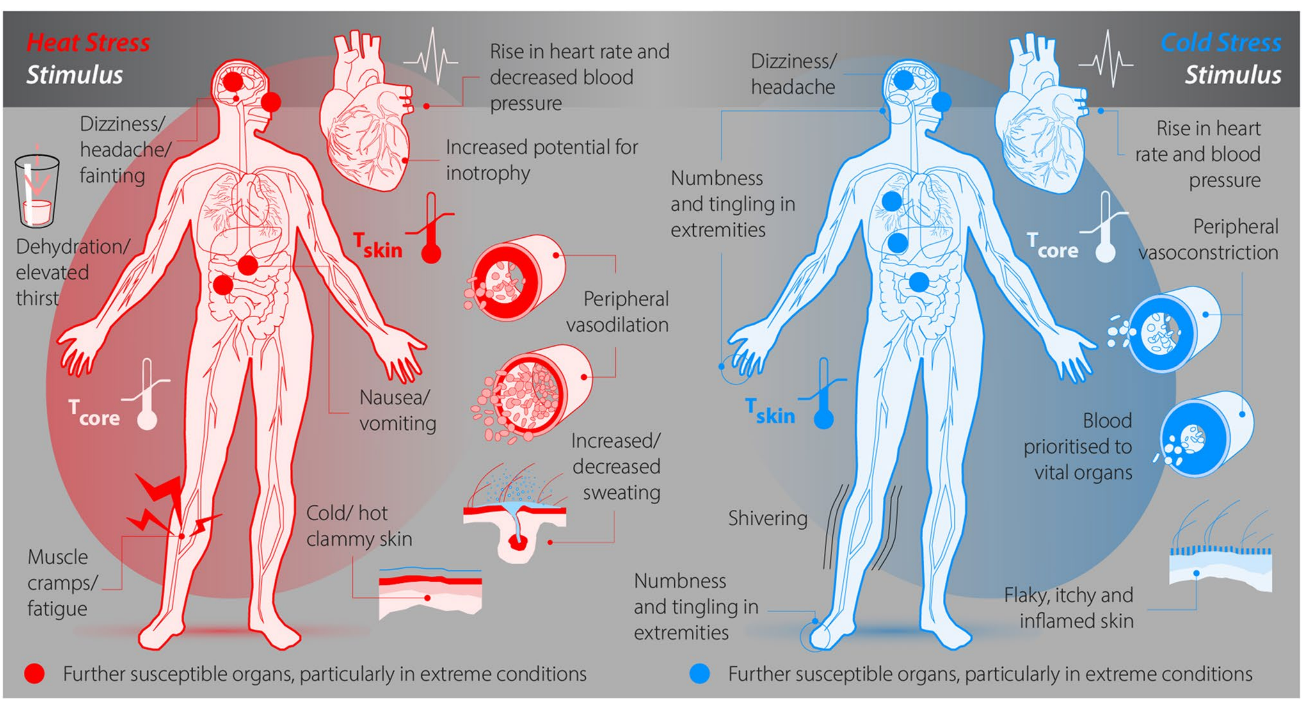


Fig. 1 Representation of human biometeorological responses to both environmental Heat Stress (HS) and Cold Stress (CS) stimulus | based on Barnett et al. (2012), Ebi et al. (2021), Kenny and Jay (2013), and White (2006)

events, the effects of low temperatures upon the biometeorological system are more complex, and usually mixed with influenza and acute respiratory grievances (Barnett et al. 2012; Davídkovová et al. 2014). In simple terms, the overarching risk factor relative to CS is when the human body loses heat faster than it can be produced. Exposure to CS causes veins and arteries to narrow (leading to peripheral constriction and re-direction of flow) with blood becoming more viscous, thus increasing the cardiac workload in a similar way to are known response to HS (Zhang et al. 2014). In addition to the sustained strain on the heart, other organs, and musculoskeletal, constricted blood flow and decreased metabolic activity due to low temperatures can moreover affect the brain, thus resulting in potential impediments to cognitive attributes and movement patterns (Pienimäki 2002; Seltenrich 2015).

While some studies have already acknowledged the significant susceptibility to both HS and CS within Ankara in relationship with the impacts on the human biometeorological system, (e.g. Çalışkan and Türkoğlu 2014; Nouri et al. 2021, 2022b; Türkoğlu et al. 2012), research into the crucial effects of urban morphology upon human thermophysiological in situ risk detection and quantification has yet to be undertaken. Centred upon the aforementioned 'human-centred approach', this study conducted an in-depth analysis into the detection and quantification of urban human thermophysiological stress within Ankara. From this approach, numerous interrelated investigative questions were depicted upon within the study, these being:

1. How the novel in situ impact assessment of urban morphological characteristics within the rapidly densifying fabric of Ankara could be conducted within the different regions of local typical canyon compositions.
2. Assessing the interchangeability between climatic top-down approaches, and how different bottom-up scaled approaches could produce a finer understanding of local climatic conditions, and moreover directly influence the human biometeorological system.
3. Determine how specific typical canyon cases within modified future urban fabric scenarios because of continued centralised urban densification patterns could lead to divergent bioclimatic conditions (including within the same canyons) during both the entire year, and moreover for the summer and winter seasons.
4. Assessing the indoor vulnerability, and its extent, associated to previous stereotypical residential construction methodologies that remain common within Ankara by depicting upon a specific representative case study during both cold/snowy winters and hot/dry summers.
5. How the results of the study could build upon the still maturing Sustainable Development Goals (SDGs) for Türkiye in terms of ensuring long-term human well-being and safety in events of moderate to extreme urban thermophysiological exposure.

2 Materials and methods

Following on from the research questions discussed in the introduction, Fig. 2 presents the summative research methodology framework. The encompassing direction of the framework aimed to identify the frequency distribution of both annual and seasonal urban thermophysiological in situ heat and cold exposure within Ankara. Such an outcome also allowed for important recognition between top-down and bottom-up biometeorological analysis perspectives, but moreover the relationship with representative indoor conditions during both the winter and summer seasons. In addition to these relationships which have received little attention in the case of Türkiye and Ankara, as previously mentioned, the main outputs of the study were also synoptically reflected upon how they can contribute towards the early Turkish SDGs.

2.1 Appraising general urban thermophysiological conditions

Given its adjacency to different seas, sizeable mountain ranges, and interior basins, Türkiye witnesses a wide array of different Köppen-Geiger Classifications (KGCs), with classifications varying between '*B*', '*C*', '*D*', and '*E*', with a further variability in sub-classifications (Rubel and Kottek 2010). As defined by the earlier study by Peel et al. (2007), the KGC of Ankara is that of '*Dsb*' which corresponds to a cold climate, with warm and dry summers, as shown in Table 1.

Finer data assessments within recent studies have however revealed that while the plateau areas within the central and eastern Anatolian regions equate to '*Dsb*', this can vary to '*Dsa*' within the depressions of the plateaus in the case of Ankara, with substantially higher temperature thresholds during the summer (Nouri et al. 2021; Yılmaz and Çiçek 2018).

From this initial top-down KGC assessment, the vulnerability to both cold and heat exposure for Ankara was already noteworthy given its cold winters, yet hot summers. Constituting the first of the three assessments of the study, overall human thermophysiological thresholds were examined.

With a temporal resolution of 1 h, between the years 2008 and 2020, the WMO station of Ankara's Meteorological Station (AMS) within the city centre (#17,130, 39°58′N 32°51′E, 886 m ASL) was utilised to process four climatic variables, these being outdoor: air temperature (Ta_O), Relative Humidity (RH_O) wind speed (at 10 m) (V_O), and cloud cover (Oct). The first two variables could be linked to the

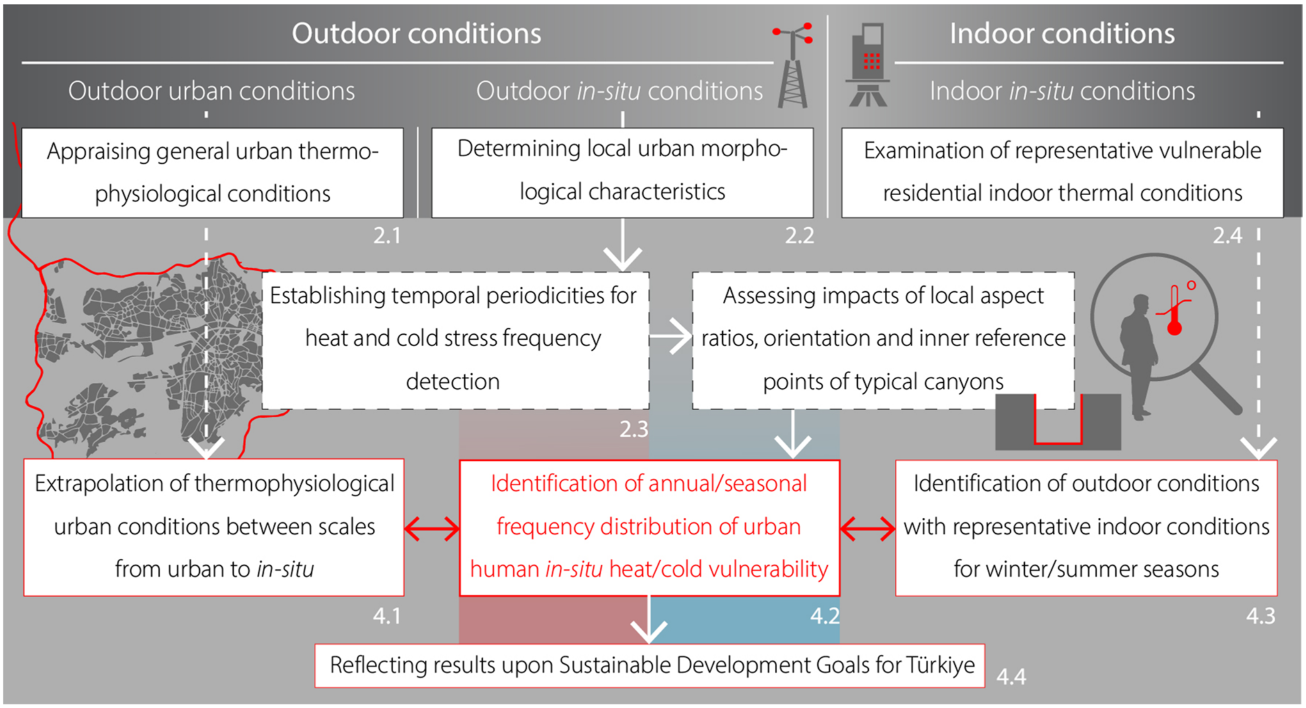


Fig. 2 Research methodology framework showing the summative collection and processing/output procedure of the different data utilised between outdoor and indoor conditions within the study sub-sections

Table 1 Descriptive environmental summary of the Köppen-Geiger classification system adapted from Peel et al. (2007)

KG class	Colloquial name of sub-classification	General classification descriptors	Specific environmental thresholds			
			Precipitation descriptors		Temperature descriptors	
			General description	Climate specification	General description	Climate specification
'*Dsb*'	Snow/cold climate with dry/warm summer	$T_{hot} \leq 21$ °C and $T_{cold} \leq 0$	Dry summer	$P_{sdry} < 40$ and $P_{sdry} < P_{wwet}/3$	Warm summer	$T_{hot} \leq 21$ °C and $T_{mon10} \geq 4$
'*Dsa*'	Snow/cold climate with dry hot summer	$T_{hot} \leq 21$ °C and $T_{cold} \leq 0$	Dry summer	$P_{sdry} < 40$ and $P_{sdry} < P_{wwet}/3$	Hot summer	$T_{hot} \geq 22$ °C
'*Csa*'	Warm temperate with dry hot summer	$T_{hot} > 10$ °C and $T_{cold} < 18$	Dry summer	$P_{sdry} < 40$ and $P_{sdry} < P_{wwet}/3$	Hot summer	$T_{hot} \geq 22$ °C
'*BSk*'	Cold semi-arid climate	$MAP < 10 \times P_{threshold}$	Steppe	$MAP \geq 5 \times P_{threshold}$	Cold	$MAT < 18$ °C

Key – *MAT*, mean annual temperature; T_{hot}, temperature of the hottest month; T_{cold}, temperature of the coldest month; T_{mon10}, number of months where the temperature is above 10; *MAP*, mean annual precipitation; P_{sdry}, precipitation of the driest month in summer; P_{wdry}, precipitation of the driest month in summer; P_{wwet}, precipitation of the wettest month in winter, $P_{threshold}$, 2 × MAT

analytical constituents of the KGCs; yet in this study, the addition of V_O and Oct permitted the inclusion of significant effects pertaining to wind dynamics and radiation fluxes. For this reason, hourly recorded Oct values were processed with the aforementioned variables within the biometeorological RayMan Pro (Fröhlich et al. 2019; Matzarakis and Fröhlich 2018; Matzarakis et al. 2010a) model to obtain Mean Radiant Temperature (MRT_O) estimations for the processed temporal period.

With regard to V_O, given that the AMS station recorded this variable at a height of 10 m, it required to be adapted to ensure its applicability to the gravity centre of the human body. Therefore, 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):

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

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

For this respective study, given the overall urban morphological composition of the urban fabric in Ankara, α was constituted at a value of 1.5. The resulting calibrated V_O values were henceforth expressed as $V1.1_O$.

The Physiologically Equivalent Temperature (PET) (Höppe 1999; Matzarakis et al. 1999; Mayer and Höppe 1987) is based upon the aforementioned MEMI, and is defined by the Ta at which, in a typical indoor setting, the human energy budget is maintained by skin and core temperature, and perspiration rates are equivalent to those under the assessed conditions. In alignment with the comparative study undertaken by de Freitas and Grigorieva (2015), the PET falls under the EBM stress classification. Such a classification encloses thermal indices, which although associated to more complex calculation routines, have been established to present better evaluations of body-atmosphere balance dynamics. Similarly, the more recent comparative analysis of thermal indices undertaken by Staiger et al. (2019) also highlighted its applicability for thermal evaluations within urban bioclimatic assessments.

The decision for the use of PET followed the rational as discussed in Nouri et al. (2017), whereby PET (i) is calibrated upon easily obtainable microclimatic input variables and (ii) uses °C as the measuring unit to asses thermal comfort thus allowing the easier interdisciplinary understanding and application for other professionals such as urban planners/designers, architects, and landscape architects to approach urban bioclimatic aspects and risk factors within different climatic contexts.

Within this study, in amalgamation with existing bioclimatic studies that have moreover examined the relationship and/or calibration of human thermophysiological indices against their original respective Physiological Stress (PS) and or thermal perception grades (e.g. Hwang and Lin 2011; Lin 2009; Nouri et al. 2021; Nouri and Costa 2017a; Potchter et al. 2018), the original grades proposed by Matzarakis et al. (1999) were synoptically expanded as presented in Table 2. However, to link such extensions for the different types of thermophysiological stress with the existing literature, different approaches were applied. In the case of CS, the added PS grades 'beyond' the original 'extreme cold stress' (CS4) threshold were established upon increments of 10 °C as applied by Matzarakis (2014) to plot PET values significantly below 4 °C for the municipality of Sankt Peter-Ording. Another example of this approach was conducted for Birobidzhan in far-east Russia, where PET thresholds below 4 °C were also categorised in increments of 10 °C to better identify the intensity of CS within the assessed environments (Bauche et al. 2013). Pertaining to HS, the expansion until HS5 was based upon the increments as defined in Nouri et al. (2018c), where based upon increments of 5 °C, two new grades were established beyond the original 'extreme heat stress' classification of > 41 °C.

Using this EBM based index, it was thus possible to extend the temperature and aridity scopes of the KGC, and categorise the equally crucial role in understanding local 'bottom-up' human thermophysiological thresholds within differing urban geo-referenced urban conditions (Andreou 2013; Charalampopoulos et al. 2016; Lin 2009; Matzarakis

Table 2 Ranges of the thermal index of Physiologically Equivalent Temperature (PET) for different grades of Physiological Stress (PS) on human beings | sources: Adapted from Matzarakis et al. (1999), with expanded cold/heat PS levels as delineated by Nouri et al. (2021)

PET* (°C)	PS level	Stress level abbreviation			Existing/added
< -20	Beyond extreme cold stress 3	CS		**(CS7)**	Added
−20 ~ −10	Beyond extreme cold stress 2			**(CS6)**	Added
−10 ~ 0	Beyond extreme cold stress 1			**(CS5)**	Added
0 ~ 4	Extreme cold stress			**(CS4)**	Existing
4 ~ 8	Strong cold stress			**(CS3)**	Existing
8 ~ 13	Moderate cold stress			**(CS2)**	Existing
13 ~ 18	Slight cold stress		NTS_{EXP}	**(CS1)**	Existing
18 ~ 23	No thermal stress	NTS		**(NTS)**	Existing
23 ~ 29	Slight heat stress			**(HS1)**	Existing
29 ~ 35	Moderate heat stress	HS		**(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 toMatzarakis and Mayer (1997)

and Amelung 2008; Nouri and Costa 2017a; Rodríguez-Algeciras et al. 2021; Rodriguez Algeciras and Matzarakis 2016; Walton et al. 2007). Such a method was relatable to the methodology conducted by Yang and Matzarakis (2016), who through the standardisation of the human biometeorological system via the PET index was also able to associate top-down KGC conditions with climatic stimulus on Physiological Stress (PS) thresholds as previously defined by Matzarakis and Mayer (1996).

To present such results, summative annual Frequency Distribution Diagrams (FDDs) were prepared upon two specific hours of the day to represent a cold hour (stipulated at 05:00), and a hot hour (stipulated at 15:00). Such a methodology permitted the communication of the frequency percentages of the PS occurrences at the specified time of day. Such approaches (as exemplified by Hwang et al. 2011; Lin et al. 2017, 2010; Nouri et al. 2021) permitted annual PS distribution and intensity to be compared within, and between, specific locations.

2.2 Determining local urban morphological characteristics

As illustrated in Table 3, similar to studies such as in Ketterer and Matzarakis (2014), Matzarakis et al. (2018b), and Nouri et al. (2017), the study configured different geometric configurations within the obstacle plugin of RayMan, where different Urban Canyon Cases (UCCs) were modelled based upon different Height-to-Width (H/W) ratios ranging between 0.25 and 3.50.

Considering the general urban consolidated fabric of Ankara, where UCC predominantly presented a recurrent width of 20 m, this remained as the constant within the H/W Ratios. On the other hand, the height of the UCCs were utilised as the augmenting variable to formulate different Aspect Ratios (ARs) to reflect the variation of different building heights. This included those already present and those that were included to account for future potential patterns of urban densification within the capital's urban centre.

Table 3 Description of utilised Aspect Ratios (ARs) depicting information into their height, width, H/W Ratio, and their typology in terms of whether they are already existent within Ankara's urban fabric or predicted as a result of future densification patterns

Canyon height (m)	Canyon width (m)	H/W Ratio	Descriptive note
5	20	0.25	Existing
10	20	0.50	
20	20	1.00	
30	20	1.50	
40	20	2.00	Densification
50	20	2.50	
60	20	3.00	
70	20	3.50	

Once constructed, and as shown in Fig. 3, each UCC hosted three Reference Points (RPs); these being (i) two lateral RPs to represent each 'sidewalk area', each 3 m away from the respective façade to symbolise lateral sidewalks (i.e. Left Lateral (LL) and Right Lateral (RL)); and (ii) one central RP (i.e. C) to portray the middle of the canyon 10 m away from either façades.

Consequently, and based upon the classic single-point Sky View Factor (SVF) methodology as disclosed in Lin et al. (2012), each RP had a resulting SVF calibrated at a height of 1.1 m, representing the gravitational centre of the human body (Kuttler 2000). The SVF represents an unbounded parameter that varies between 0 (representing no visible sky) and 1 (representing a free hemisphere), and thus expresses the fraction of the hemisphere that is exposed to the sky (Oke 1978, 1981). Through this methodology, it was possible to distinguish three separate in situ locations to differentiate the exposure to radiation fluxes because of both the urban obstacles and solar path.

Furthermore, for each AR, 12 different orientations were simulated with a variation of 15° to account for the high variability of UCC's intrinsic to Ankara's urban fabric. Thus, and as represented in Appendix Figures 9 and 10, each of the orientations were overlaid to represent general exposure to the sky in relationship to both the winter and summer solstice extremes for the shortest day (December the 22nd) and longest day (i.e. the 21st of July) of the year.

Relaying to previous studies (e.g. Abreu-Harbich et al. 2013; Herrmann and Matzarakis 2012; Ndetto and Matzarakis 2013; Nouri et al. 2017), the emphasis of such a methodology was to identify how different UCC characteristics (i.e. width, height, and orientation) would lead to different environmental conditions, including that of radiation fluxes. Relative to the general assessment of human thermophysiological conditions in the first assessment, the same local hourly meteorological variables (i.e. Ta_O, RH_O, $V1.1_O$, and Oct) for Ankara's urban centre were again processed with moreover the aid of R language scripts (Charalampopoulos 2020). The principal differentiation for this approach was the use of AMS data to construct a baseline of local environmental conditions that would be altered because of the morphological characteristics of each UCC and RP.

2.3 Establishing temporal periodicities for heat and cold stress frequency detection

As shown in Appendix Figures 9 and 10, specific hours were highlighted as they were used to determine the frequency and intensity of measured CS and HS grades during the different times of the year. Such an assessment was subdivided into three temporal categories as characterised in Table 4.

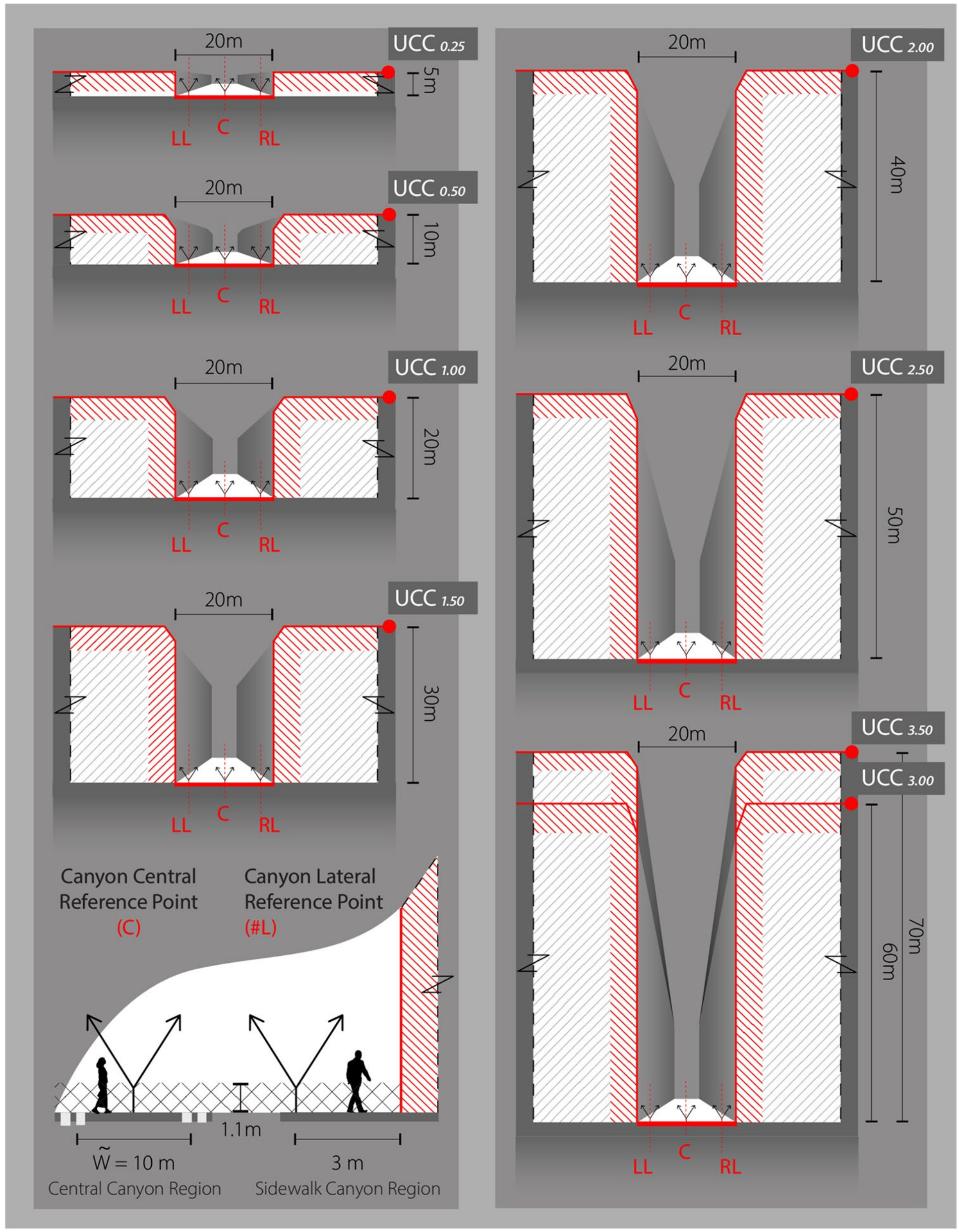
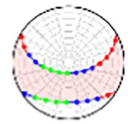
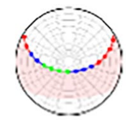
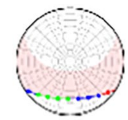


Fig. 3 Distribution of the different Reference Points (RPs) within the eight configured Aspect Ratios (ARs)

To determine the in situ human thermophysiological conditions in Ankara, three types of assessments were undertaken. Firstly, and similar to the methodology in Ketterer and Matzarakis (2014), PS levels for all months of the year between 2008 and 2020 were assessed. However, in addition to running the added lateral reference points within this study, the yearly evaluation was also undertaken during specific diurnal hours, rather than all hours of the day. More concisely, average PET_O values were calculated for the Diurnal Period (DP) between the hours of 09:00 and 17:00 (henceforth DP_I), within a frequency window of 10 days, for the entire year. The selected frequency window was established for two predominant reasons: (i) to establish a frequency window large enough to evaluate the hourly data, and yet small enough to present three assessments every calendar month; and in association, (ii) maintain the same temporal window as conducted for the identification of the general human thermophysiological conditions for Ankara. From this assessment, the frequency of three types of human PS as presented in Table 2 was undertaken for each of the UCCs and RPs. However, to augment the thresholds indicative of No Thermal Stress (NTS), with both CS1 (indicative of slight cold stress where PET values oscillate between 13.1 and 18.0 °C) and HS1 (indicative of slight heat stress where PET values oscillate between 23.1 and 29.0 °C). As a result, and with the aim of accepting slight variations within the original NTS threshold (hereafter referred to as NTS_{EXP}), the classification was expanded to range from 13.1 to 29.0 °C.

Table 4 Temporal evaluation of seasonal and yearly human thermophysiological conditions based upon Physiological Stress (PS) frequency and intensity

	All Year			Summer	Winter
Solstice Representation					
Yearly Dataset	[2008 – 2020]			[2008 – 2020]	[2008 – 2020]
Dataset Res.	Hourly			Hourly	Hourly
Utilised Months	[1 – 12]			[6 – 8]	[12-2]
Frequency	10 Days			10 Days	10 Days
Diurnal Period Window	09:00 – 17:00 (DP_1) 			12:00 – 15:00 (DP_2) 	12:00 – 15:00 (DP_2) 
PS Focus Type	CS, NTS, HS			HS	CS
PS Class Range	CS > CS2	NTS_{EXP} CS1, NTS, HS1	HS > HS2	> HS2	> CS2
PET Range	CS ≤ 13.0 ºC	NTS_{EXP} 13.1 ºC - 29.0 ºC	HS ≥ 29.1 ºC	≥ 29.1 ºC	≤ 13.0 ºC

Surpassing these boundaries, values outside this range were associated to environmental conditions with equal or higher levels of moderate CS or HS.

The subsequent assessments focused specifically upon the identification and quantification of both CS and HS frequency within the UCCs and RPs during the summer and winter seasons. In contrast with the first assessment, a shorter DP was successively utilised to extrapolate average PET values during the hotter hours of the day, i.e. between 12:00 and 15:00 (henceforth DP_2). For the case of the summer season, the frequency of environmental conditions with PET values ≥ 29.1 °C, i.e. equal or superior to HS2, was assessed between the months of June and August. For the winter period, the same DP_2 hours were utilised to assess the frequency period of environmental conditions where PET values were below ≤ 13.0 °C, i.e. equal or superior to a CS2 for the months between December and February.

2.4 Examination of representative vulnerable residential indoor thermal conditions

The final assessment conducted within the study was directed at associating indoor environmental conditions with those processed from outdoors. To undertake this analysis, a representative residential construction typology was selected to assess vulnerable, yet very frequent, dwellings in Ankara. These dwellings consist of previous traditional methods entailing a reinforced concrete structure system with hollow clay bricked external/internal walls hosting a cement plaster finish, with a load-bearing skeleton, composed of reinforced concrete floors without any outer shell insulation (Esiyok 2006; Nouri et al. 2022a). The disclosed construction methods reflect those prior to the introduction of building insulation and performance standards in 2008 in an effort to match construction European Union performance norms (Gültekin and Farahbakhsh 2016).

As a result, this presented the opportunity to assess seasonal environmental conditions within a typical thermally vulnerable, yet highly common residential typology in Ankara. Although the case study utilised a central heating system during the winter, it lacked any type of TACs, and depended only upon natural ventilation during the summer. For both the winter and summer period, at a finer measurement resolution of 10 min, all outdoor variables were recorded indoors using an interior Kestrel Heat Stress (KHS) station (Appendix Table 5). The only difference was the collection of Oct, which was replaced with indoor Globe Temperature (Tg_I) to calculate MRT_I using the formula as defined by the ISO-7726 (1998):

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

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)

For the summer season, indoor recordings were undertaken for the months of July and August of 2020, and December and January of 2020/2021 for the winter period. The KHS was placed in the centre of a second-storey south-western facing apartment of approximately 45 m^2, where the exterior building shell (with a high U-value of 1.7 W/m^{2}K) received almost constant direct exposure to the sun with summer a solstice on its southern façade in the morning period (≙ 06:00–12:00), and western façade in the afternoon period (≙ 12:00–19:00) (Nouri et al. 2022a). To compare the calculated PET values between indoors and outdoors in the study, Maxima and Minima were calculated for all days during each of the 2 months from both respective seasons. Through this approach, it was possible to moreover sample how indoor human thermophysiological conditions also faired against seasonal environmental conditions. Such a methodology is concomitant with the growing epidemiologic recognition of, in addition to using local MS data, the required use of in situ indoor measurements to moreover determine the symbiotic urban cause-and-effect effects upon interior contexts (Basu and Samet 2002; Matzarakis 2021; Nazaroff 2008; Smargiassi et al. 2008; White-Newsome et al. 2012).

3 Results

3.1 General human thermophysiological conditions for Ankara

As shown in Fig. 4, the first assessment of the study revealed the considerable oscillation in human thermophysiological levels between 2008 and 2020 for the city centre for both the hottest and coldest hours of the day, i.e. 15:00 and 05:00, respectively. Moreover, given the expanded PS grades as disclosed in Table 1, it was possible to examine the frequency of levels that went beyond the original thresholds, particularly in the case of CS.

It was possible to better determine the frequency of CS levels when PET_O values went considerably below 4 °C (i.e. CS4). Even at 15:00, December and January revealed that the combined frequency of CS5 and CS6 (i.e. of PET_O values ranging between 0.0 and − 19.9 °C) oscillated from 16.0% up to a considerable 52.0%.

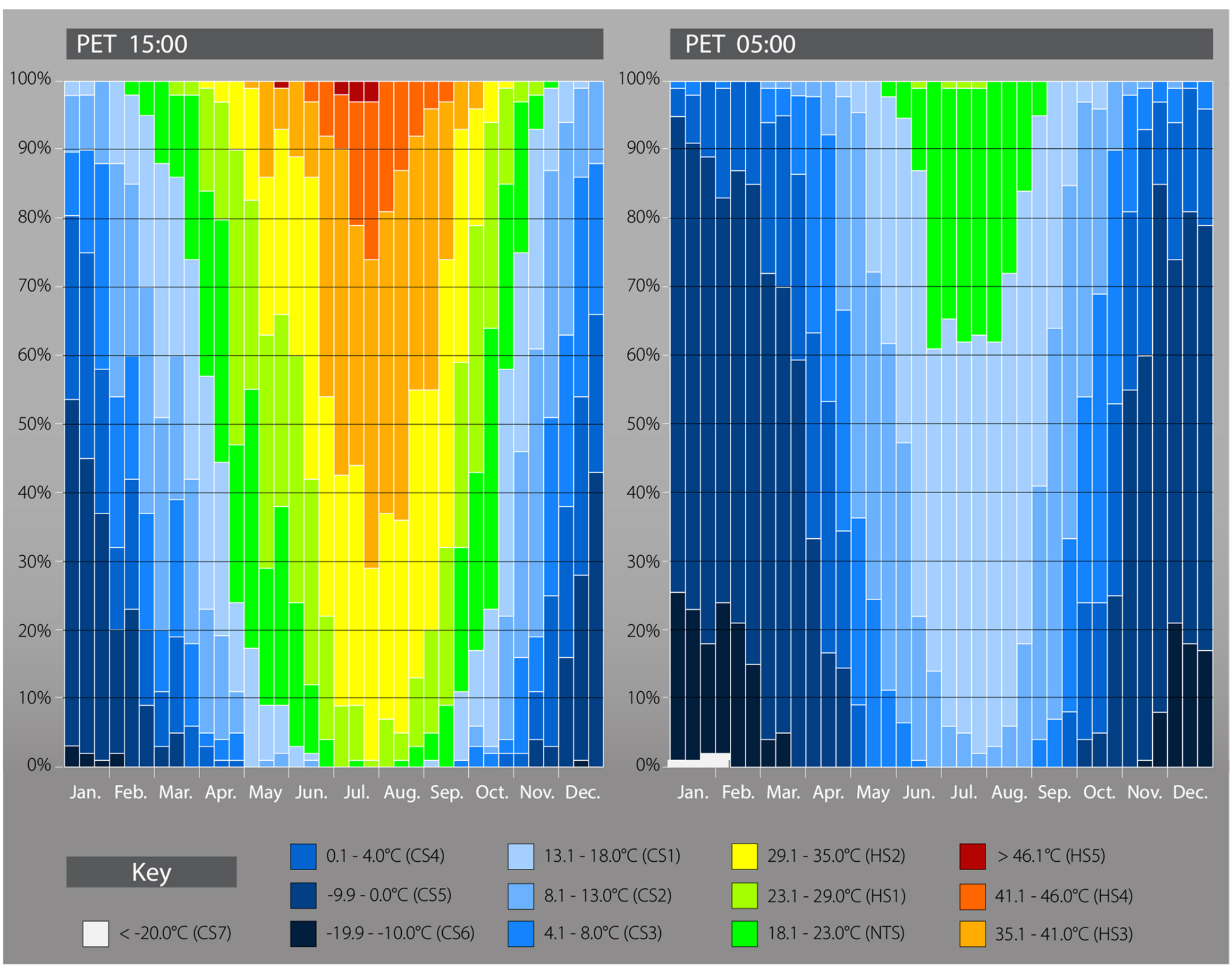


Fig. 4 Frequency distribution of PS grades for PET between 2008 and 2020 at 15:00 and 05:00 for Ankara's city centre

On the other hand, as to be expected, nocturnal frequencies of such grades were a lot higher, with the added low, yet notable, susceptibility to CS7 (i.e. representing conditions with $PET_O < -20$ °C) that ranged between 1.0 and 2.0% for January and early February. Between December and February, the combined frequency of CS5 and CS6 constantly remained above 70%, with CS6 frequency surpassing 20%. When isolating the case of January, the combination of CS5 and CS6 almost always remained above 90%, as did CS6 above that of 20%.

When considering the exposure to environmental HS conditions, it was possible to identify noteworthy exposure within the urban centre during the summer months as well. Most of the higher susceptibility to HS was identified between mid-June and early September. Between this period, 15:00 revealed exposure to HS3 through to HS5, with HS5 (i.e. corresponding to conditions with $PET_O > 46.1$ °C) ranging up to 3% mid-summer during the month of July. More significantly however was the (i) combination of HS3 and HS4 (i.e. of PET_O values ranging between 35.1 and 46.0 °C) which varied between 46 and 68%; (ii) frequency of HS4 ranging between 18 and 23%; and lastly, (iii) the practically lack of any CS for entirety for the same summer period. Building upon the latter, from late June to mid-August, the colder nocturnal hour of 05:00 still revealed a NTS frequency oscillating between 28 and 37%, with the remaining frequency predominantly revealing CS1 (i.e. of PET_O values ranging between 13.1 and 18.0 °C).

3.2 Urban morphological effects upon thermophysiological conditions

Within the second part of the study, it was possible to determine oscillations of seasonal outdoor human thermophysiological conditions based upon two diurnal periods as delineated in Table 4 (i.e. these being: DP_1—referring to the diurnal hours between 09:00 and 17:00, and DP_2—referring to the hotter hours between 12:00 and 15:00). As demonstrated in Fig. 5, the annual frequency of different environmental conditions varied considerably depending upon the different urban morphological settings. As to be expected, the largest impact upon human thermophysiological thresholds was the oscillation in AR. However, the frequency variation between CS, NTS_{EXP}, and HS conditions were considerably dissimilar between $UCC_{0.25}$ and $UCC_{3.50}$.

As presented in Fig. 6, such dissimilarities presented important results between the different RPs, UCC orientations, and amid the thermophysiological thresholds. Regarding the latter, it was feasible to identify that environmental HS amid $UCC_{0.25}$ and $UCC_{3.50}$ presented the highest oscillation in frequency. More specifically, it was possible to verify that HS frequency was reduced by up to 7.1% (114 min) in this location as demonstrated by RP_C within a UCC orientation of 90° (hereafter expressed as RP_COR_{90}). Within these canyons, both RP_C and RP_{RL} represented the in situ locations with the highest differences between the ARs, particularly between orientations 0° through to 90°. When considering NTS_{EXP} conditions, even stronger in situ disparities could be identified. UCCs with orientations between 75 and 165° revealed that RP_{LL} had a considerably higher oscillation in comparison to the other locations within the UCCs. As exemplified by $RP_{LL}OR_{105}$, although within the same UCC, annual NTS_{EXP} frequency decreased by 1.9% (30 min) in comparison to RP_COR_{105}, and 2.5% (40 min) relative to $RP_{RL}OR_{105}$. Given the relatively limited variation of NTS_{EXP} frequency in RP_{RL} between $UCC_{0.25}$ and $UCC_{3.50}$, disparities of such environmental conditions in the same canyon became more noteworthy.

Finally, with regard to CS conditions, significant frequency variability was also identified. While RP_C and RP_{RL} presented limited frequency oscillation from one another, and between all orientations, this was not the case of RP_{LL}. As presented by $RP_{LL}OR_{75}$ and $RP_{LL}OR_{90}$, the change in CS frequency was significant in comparison to not only other orientations, but other locations within the canyon as well. As exemplified by $RP_{LL}OR_{90}$, there was a limited frequency oscillation of 0.6% between $UCC_{0.25}$ and $UCC_{3.50}$. However, within the same orientation, both RP_C and RP_{RL} revealed notably higher variations of 4.2% and 4.4% (an average of 69 min).

The distribution of environmental HS and CS during DP_2 during the summer and winter seasons is presented in Fig. 7. The results enabled the identification of which UCCs, and just as importantly which RPs, presented higher human thermophysiological susceptibility. As recognised for annual exposure, the same expected type of pattern could be identified between $UCC_{0.25}$ and $UCC_{3.50}$, where the lower ARs presented higher HS and lower CS frequencies (and vice versa).

However, the results also revealed the crucial impacts of both orientation and RP locations between the different UCCs. It was acknowledged that the orientations with the highest HS frequency were UCCs with orientations between that of 105° and 135°. Within these canyons, even in the $UCC_{3.50}$, the frequency of HS almost always remained over 72% (2592 min). The reason for this could be directly attributed to the implications of the summer solstice (Appendix Figures 9 and 10). Although $UCC_{3.00}$ and $UCC_{3.50}$ received less exposure to radiation, the partial DP_2 exposed to the sun during the hotter hours of the day still augmented the frequency of in situ environmental HS.

In addition, in orientations which presented less overall HS frequencies, such as UCCs with an orientation of 60° and 75°, it was possible to witness considerable reductions of around 6% (230 min) as exemplified by $UCC_{1.50}RP_COR_{75}$

Orientation	RP		0.25	0.50	1.00	1.50	2.00	2.50	3.00	3.50
Orientation (0º)	LL	CS	27.0	27.5	28.8	29.3	29.6	29.8	30.0	30.1
		NTS	48.6	49.7	49.3	49.8	50.2	50.2	50.0	50.6
		HS	24.4	22.8	21.8	20.9	20.1	20.0	20.0	19.3
	C	CS	25.8	27.1	28.8	29.4	29.8	29.9	30.0	30.1
		NTS	48.2	48.0	49.4	49.7	50.2	50.8	50.6	50.7
		HS	26.0	24.8	21.8	20.8	20.0	19.3	19.3	19.2
	RL	CS	26.6	27.8	28.8	29.5	29.6	29.8	30.0	30.0
		NTS	47.9	48.4	50.0	50.1	50.3	50.3	50.6	50.7
		HS	25.5	23.7	21.2	20.3	20.0	19.8	19.5	19.2
Orientation (15º)	LL	CS	27.3	27.6	28.9	29.3	29.6	29.8	30.0	30.0
		NTS	48.4	49.8	49.2	49.5	49.6	50.5	50.3	50.3
		HS	24.3	22.6	21.9	21.2	20.7	19.7	19.7	19.6
	C	CS	26.0	27.3	28.7	29.4	29.6	29.6	29.8	30.0
		NTS	47.9	47.9	49.1	49.7	50.3	50.3	50.2	50.4
		HS	26.1	24.9	22.3	20.8	20.1	20.0	20.0	19.7
	RL	CS	26.2	27.7	28.8	29.3	29.7	29.8	30.0	30.1
		NTS	48.1	48.6	49.2	50.2	50.2	50.8	50.6	50.8
		HS	25.7	23.7	22.0	20.4	20.1	19.5	19.4	19.1
Orientation (30º)	LL	CS	27.5	28.2	29.0	29.5	29.6	29.8	29.7	30.0
		NTS	48.4	49.3	49.3	49.5	49.6	49.5	50.6	50.3
		HS	24.0	22.5	21.7	21.0	20.7	20.7	19.6	19.7
	C	CS	26.1	27.3	28.7	29.3	29.4	29.7	29.9	30.1
		NTS	47.8	47.9	49.2	50.3	50.1	50.3	50.8	50.3
		HS	26.1	24.8	22.0	20.3	20.4	20.0	19.3	19.5
	RL	CS	26.1	27.1	28.7	29.3	29.6	29.7	29.9	30.0
		NTS	48.1	48.3	49.3	49.7	50.1	50.2	50.1	50.3
		HS	25.7	24.6	22.0	20.9	20.3	20.1	20.0	19.7
Orientation (45º)	LL	CS	28.0	28.7	29.0	29.7	29.7	29.9	30.1	30.2
		NTS	48.0	49.1	49.3	49.2	49.5	50.1	50.1	50.1
		HS	24.0	22.1	21.7	21.1	20.8	20.0	19.8	19.7
	C	CS	26.1	27.6	28.9	29.4	29.9	29.9	30.1	30.2
		NTS	47.7	47.5	48.6	49.3	49.4	49.3	49.4	49.8
		HS	26.2	25.0	22.5	21.2	20.7	20.7	20.4	20.0
	RL	CS	26.0	27.1	28.7	29.4	29.6	29.8	30.0	30.1
		NTS	47.9	47.9	48.3	49.3	49.6	49.9	50.0	50.1
		HS	26.1	25.0	23.0	21.3	20.7	20.3	20.0	19.8
Orientation (60º)	LL	CS	27.8	28.9	29.6	29.8	30.0	30.1	30.3	30.3
		NTS	47.8	49.4	49.8	49.9	49.8	49.8	49.8	50.1
		HS	24.4	21.7	20.6	20.3	20.2	20.0	20.0	19.6
	C	CS	26.1	28.1	29.3	29.8	29.9	30.0	30.2	30.2
		NTS	47.5	46.6	48.2	48.9	49.3	49.6	49.7	50.0
		HS	26.4	25.3	22.5	21.3	20.8	20.4	20.0	19.7
	RL	CS	26.0	27.1	28.9	29.6	29.9	29.9	29.9	30.2
		NTS	47.9	47.4	47.3	48.2	48.9	49.2	50.1	49.6
		HS	26.1	25.6	23.8	22.1	21.3	20.8	20.0	20.2
Orientation (75º)	LL	CS	28.8	29.0	29.6	29.9	30.0	30.1	30.3	29.4
		NTS	46.8	49.6	50.3	50.7	50.8	50.7	50.7	51.0
		HS	24.4	21.4	20.1	19.4	19.2	19.1	19.0	19.6
	C	CS	26.1	28.3	29.4	29.9	30.0	30.1	30.3	30.3
		NTS	47.4	46.0	47.5	49.0	49.5	49.8	49.8	50.1
		HS	26.4	25.6	23.1	21.1	20.5	20.1	19.9	19.5
	RL	CS	26.2	27.3	29.2	29.8	30.0	30.1	30.3	30.2
		NTS	47.9	47.1	46.3	47.1	48.0	48.8	49.1	49.6
		HS	25.9	25.6	24.5	23.1	22.0	21.0	20.5	20.2
Orientation (90º)	LL	CS	28.8	29.1	29.6	29.9	30.1	30.1	30.3	29.4
		NTS	46.7	48.9	50.2	50.4	50.3	50.7	50.4	51.0
		HS	24.5	22.1	20.1	19.7	19.7	19.1	19.3	19.6
	C	CS	26.1	28.5	29.4	29.9	30.1	30.1	30.3	30.3
		NTS	47.4	45.6	47.3	48.5	49.7	50.0	50.3	50.4
		HS	26.4	25.8	23.2	21.6	20.3	19.9	19.5	19.3
	RL	CS	25.9	27.5	29.2	29.9	30.0	30.1	30.3	30.3
		NTS	48.0	46.9	46.5	47.1	47.9	48.5	49.3	49.8
		HS	26.1	25.6	24.3	23.0	22.1	21.4	20.4	19.8
Orientation (105º)	LL	CS	28.7	28.9	29.6	29.9	30.0	30.1	30.3	30.3
		NTS	46.3	48.9	49.6	49.6	49.7	50.3	50.3	50.5
		HS	25.0	22.1	20.8	20.5	20.2	19.6	19.4	19.2
	C	CS	25.8	28.9	29.4	29.8	30.0	30.1	30.2	30.3
		NTS	47.8	48.9	47.3	49.1	49.6	49.9	50.1	50.1
		HS	26.4	22.1	23.3	21.1	20.4	20.0	19.7	19.6
	RL	CS	25.9	29.3	29.3	29.7	30.0	30.0	30.2	30.3
		NTS	48.3	47.6	46.8	47.5	48.6	49.3	49.6	49.9
		HS	25.8	23.0	24.0	22.8	21.4	20.7	20.1	19.9
Orientation (120º)	LL	CS	28.7	28.9	29.5	29.7	30.0	30.0	30.2	30.2
		NTS	46.3	48.9	49.1	50.1	50.0	50.0	50.1	50.2
		HS	25.0	22.1	21.4	20.2	20.0	19.9	19.7	19.7
	C	CS	25.8	28.0	29.3	29.7	29.9	30.0	30.2	30.2
		NTS	47.8	46.5	48.3	49.3	49.5	49.8	49.8	49.9
		HS	26.4	25.4	22.4	21.0	20.6	20.2	20.0	19.9
	RL	CS	25.9	27.0	29.0	29.5	29.8	29.9	30.1	30.2
		NTS	48.6	48.3	47.3	48.1	49.2	49.9	50.0	50.0
		HS	25.4	24.7	23.7	22.4	20.9	20.2	19.9	19.8
Orientation (135º)	LL	CS	27.8	28.6	29.4	29.7	29.8	29.8	30.0	29.4
		NTS	47.2	48.4	49.7	49.4	49.9	50.0	49.9	51.0
		HS	25.0	23.0	20.9	20.8	20.2	20.2	20.1	19.6
	C	CS	25.8	27.5	29.0	29.5	29.8	29.7	30.0	30.1
		NTS	47.9	47.4	49.0	49.4	49.4	50.1	50.2	50.3
		HS	26.3	25.1	21.9	21.1	20.8	20.1	19.8	19.5
	RL	CS	26.1	27.0	28.8	29.4	29.8	29.7	30.0	30.1
		NTS	48.4	48.5	48.3	49.2	49.9	50.3	50.2	50.4
		HS	25.4	24.5	22.9	21.4	20.3	19.9	19.8	19.5
Orientation (150º)	LL	CS	27.4	28.1	29.0	29.4	29.5	29.7	29.9	29.4
		NTS	47.4	49.0	49.6	49.8	49.7	50.6	50.6	51.0
		HS	25.2	22.9	21.3	20.8	20.8	19.7	19.5	19.6
	C	CS	25.8	27.5	28.7	29.2	29.6	29.7	29.9	30.0
		NTS	48.0	47.5	49.4	50.4	50.4	50.5	50.4	50.5
		HS	26.2	25.0	21.9	20.4	20.0	19.8	19.6	19.5
	RL	CS	26.3	27.0	28.7	29.3	29.6	29.7	30.0	30.1
		NTS	48.7	49.4	48.7	49.5	50.2	50.5	50.5	50.7
		HS	25.0	23.6	22.5	21.2	20.2	19.8	19.4	19.2
Orientation (165º)	LL	CS	27.2	28.0	29.0	29.2	29.6	29.6	29.7	29.4
		NTS	47.6	49.0	49.8	50.0	50.6	50.7	50.6	51.0
		HS	25.3	23.0	21.1	20.7	19.8	19.6	19.6	19.6
	C	CS	25.9	27.2	28.9	29.3	29.7	29.7	29.9	30.1
		NTS	48.0	47.9	49.4	50.1	50.1	50.6	50.8	50.7
		HS	26.1	24.9	21.7	20.6	20.2	19.7	19.3	19.2
	RL	CS	26.6	27.2	28.9	29.4	29.7	29.9	30.0	30.2
		NTS	48.6	49.2	49.3	49.7	50.1	50.4	50.5	50.6
		HS	24.8	23.6	21.8	20.8	20.1	19.7	19.4	19.2

Fig. 5 Frequency distribution of annual CS, NTS_{EXP}, and HS within the different UCCs, and canyon RPs in association to each orientation with an hourly resolution associated to the DP_1 between the years 2008–2020 through the adapted human thermophysiological thresholds

and $UCC_{2.50}RP_{RL}OR_{75}$. Similarly, these locations presented more pronounced variations within the canyons themselves, where frequencies of HS also varied up to 6% between the different RPs of the canyon.

Another result was that the specification of the RPs allowed for a greater precision of HS patterns between the different ARs, and thus shedding more light upon impacts of the different urban morphological settings. While $UCC_{0.25}$ and $UCC_{0.50}$ only had a difference of 5 m on either side of the canyon (Fig. 3), in numerous orientations, HS in RP_{LL} varied by up to 8.4% (302 min). Such reductions were always lower within RP_C and RP_{RL}. This led to the

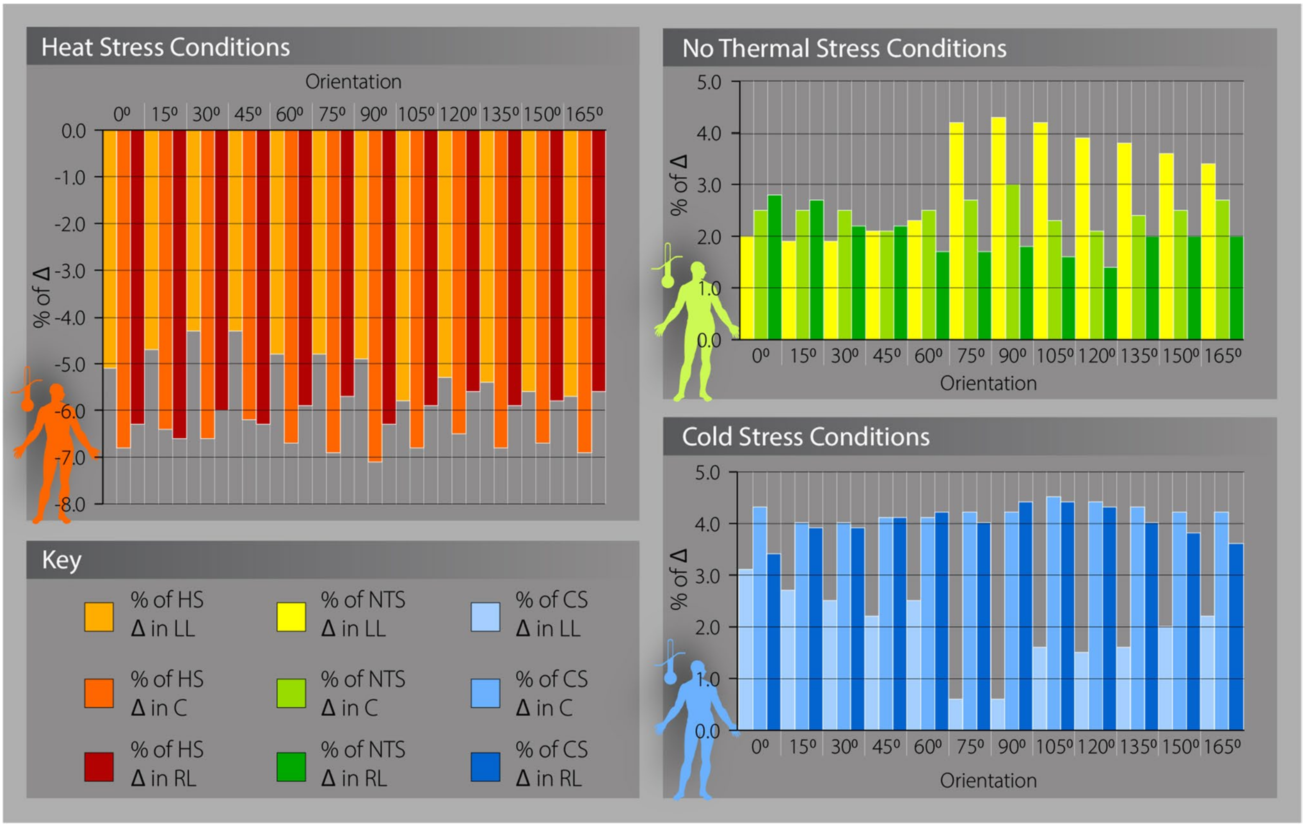


Fig. 6 Change in frequency distribution between $UCC_{0.25}$ and $UCC_{3.50}$ for annual HS, NTS_{EXP}, and CS between the different orientations associated to the DP_I between the years 2008–2020

important validation that lower ARs could still present lower HS frequencies then those attributable to higher ARs. Such a recurring incidence was exemplified by $UCC_{2.50}RP_{RL}OR_{90}$ presenting a HS frequency of 76.0% (2736 min) in contrast to the 75.1% as identified in $UCC_{0.50}RP_{LL}OR_{90}$. It was significant to note that the canyon height of $UCC_{2.50}$ was of 50 m; in juxtaposition, the canyon height of $UCC_{0.50}$ was of 10 m (Table 3).

When considering CS frequency for the winter months, it was possible to identify similar frequency oscillations between RP_{LL} and the other two canyon areas, particularly for orientations between 0 and 135°. Within $UCC_{0.25}$, RP_C and RP_{RL} consistently presented similar CS frequencies that ranged up to 69.4% (2498 min); on the other hand, RP_{LL} presented up to an additional 5.3% (191 min).

It was clear that the orientations which presented less CS environmental frequency were orientations 135° through to 0°, particularly in 150° and 165°, and within RP_{LL} and RP_C which showed little increase in CS occurrence after $UCC_{2.00}$. Notwithstanding, it was noted that such orientations with lower CS frequencies had a restricted connection with those presenting higher HS frequencies, as exemplified by orientations 105° through to 135°. Invariably, such a result paid tribute to the divergent annual effect of the winter and summer solstice upon the disclosed UCCs.

3.3 Urban indoor thermophysiological conditions

As stated within the aims and methodology of the study, the third step was to take a representative sample of how urban outdoor conditions affected a residential typology with prior construction methods that no longer meet required national building codes. Such a dwelling typology was selected both due to its elevated occurrence within the urban fabric of Ankara, but in addition, to its vulnerability to exterior climatic conditions.

In Fig. 8(A), the results between the correlation of indoor and outdoor PET oscillations were presented. It is possible to identify that maximum PET_I values reached 30 °C, particularly when maximum PET_O values exceeded 40 °C, and minimum PET_O values remained above 15 °C. Such an occurrence can be interrelated with days with particularly elevated outdoor HS conditions, and where subsequent tropical nights would not allow the absorbed diurnal heat to effectively dissipate.

Orient.		HS 0.25	HS 0.50	HS 1.00	HS 1.50	HS 2.00	HS 2.50	HS 3.00	HS 3.50		CS 0.25	CS 0.50	CS 1.00	CS 1.50	CS 2.00	CS 2.50	CS 3.00	CS 3.50
Orient. (0º)	LL	82.6	77.9	73.8	72.3	71.5	71.3	70.9	70.3	LL	72.1	74.4	76.2	76.1	76.5	76.8	76.7	77.0
	C	85.0	82.6	77.1	75.1	71.7	71.3	71.0	70.8	C	66.7	70.8	74.3	76.0	76.1	76.6	76.6	76.9
	RL	83.8	81.6	78.7	75.8	74.1	73.5	71.2	70.8	RL	67.8	70.1	73.4	74.3	75.8	76.6	76.5	76.9
Orient. (15º)	LL	82.5	76.2	73.4	71.4	70.4	70.0	69.7	69.4	LL	74.0	75.4	77.0	77.1	77.7	78.0	77.8	77.8
	C	85.0	82.6	77.1	75.1	71.6	71.3	71.1	70.7	C	67.5	72.3	76.1	76.0	77.6	78.0	77.8	77.8
	RL	83.8	81.5	78.7	75.2	73.5	71.3	71.0	70.8	RL	68.0	70.6	74.9	76.1	76.6	77.5	77.7	77.8
Orient. (30º)	LL	82.6	75.9	72.8	71.4	70.4	70.0	69.7	69.4	LL	74.6	75.5	77.2	77.1	77.7	78.0	77.8	77.8
	C	85.0	82.6	76.5	72.6	71.3	70.7	69.7	69.4	C	68.3	74.1	77.1	76.7	77.8	78.0	77.8	77.8
	RL	83.8	81.6	78.9	78.9	75.2	71.3	70.9	70.6	RL	68.3	71.3	76.5	77.1	77.7	78.0	77.8	77.8
Orient. (45º)	LL	82.6	75.5	72.8	71.3	70.4	69.9	69.7	69.5	LL	74.7	75.5	77.2	77.1	77.7	78.0	77.7	77.8
	C	85.0	82.6	76.4	72.4	70.8	70.1	69.7	69.4	C	69.4	74.8	77.1	77.0	77.8	78.0	77.8	77.8
	RL	83.8	81.6	79.5	75.0	72.8	71.2	70.6	69.8	RL	68.0	72.4	77.2	77.1	77.7	78.0	77.7	77.8
Orient. (60º)	LL	82.9	75.3	72.8	71.5	70.4	70.0	69.7	69.4	LL	74.7	75.5	77.2	77.1	77.7	78.0	77.8	77.8
	C	84.9	82.7	77.6	72.3	70.5	69.9	69.7	69.4	C	68.7	75.2	77.1	77.0	77.6	78.0	77.8	77.8
	RL	83.8	81.6	79.6	77.7	73.1	70.9	70.9	69.4	RL	68.3	72.9	77.2	77.1	77.7	78.0	77.8	77.8
Orient. (75º)	LL	83.5	75.1	72.8	71.3	70.4	70.0	69.6	69.5	LL	74.7	75.5	77.2	77.1	77.7	78.0	77.7	77.8
	C	85.0	82.7	78.6	72.2	70.5	70.1	69.7	69.4	C	68.9	75.2	77.1	77.0	77.6	78.0	77.8	77.8
	RL	83.8	81.6	79.7	77.7	76.0	70.9	69.7	69.4	RL	68.3	72.9	77.2	77.1	77.7	78.0	77.8	77.8
Orient. (90º)	LL	83.8	75.1	73.2	71.4	70.3	70.0	69.7	69.4	LL	74.7	75.5	77.2	77.1	77.7	78.0	77.8	77.8
	C	85.0	82.7	79.4	77.2	73.6	71.3	71.0	70.0	C	68.9	75.2	77.1	77.0	77.6	78.0	77.7	77.8
	RL	83.8	81.6	79.7	78.8	76.8	76.0	73.7	71.9	RL	68.7	73.0	77.2	77.1	77.7	78.0	77.8	77.8
Orient. (105º)	LL	83.8	80.9	76.8	74.3	73.2	71.7	71.5	71.1	LL	74.7	75.5	77.2	77.1	77.7	78.0	77.8	77.8
	C	85.0	82.7	80.0	78.4	76.2	75.1	73.6	73.2	C	66.4	74.7	77.1	77.0	77.6	78.0	77.8	77.8
	RL	83.8	81.5	79.7	77.8	77.0	76.2	74.7	74.2	RL	67.6	70.9	77.2	77.1	77.7	78.0	77.9	77.8
Orient. (120º)	LL	83.8	80.9	78.5	76.9	74.9	73.5	72.7	72.6	LL	74.7	75.5	77.2	77.1	77.7	78.0	77.7	77.8
	C	85.0	82.7	80.0	78.1	76.2	75.6	74.6	74.4	C	66.4	72.8	77.0	77.0	77.6	78.0	77.8	77.8
	RL	83.8	80.7	78.7	77.5	75.3	74.4	73.6	72.8	RL	67.6	69.3	75.7	76.9	77.6	77.8	77.7	77.8
Orient. (135º)	LL	83.8	81.4	79.3	77.6	75.6	75.2	74.6	73.6	LL	71.5	74.3	76.2	76.4	76.7	76.8	77.0	77.3
	C	85.0	82.7	79.2	77.4	76.3	74.0	73.0	72.6	C	66.2	70.5	74.5	76.1	76.3	76.9	76.9	77.3
	RL	83.8	80.6	77.2	75.1	73.8	73.7	73.2	72.9	RL	67.6	69.3	73.1	75.0	76.2	76.8	77.2	77.5
Orient. (150º)	LL	83.8	81.6	79.6	76.8	75.8	73.2	72.5	72.2	LL	69.3	72.2	74.3	75.1	75.5	76.0	76.0	76.0
	C	84.9	82.7	79.0	75.5	74.4	73.7	73.2	72.9	C	66.2	69.2	72.8	74.6	75.3	76.0	76.1	76.2
	RL	83.8	79.0	76.8	73.9	72.4	72.1	71.5	71.2	RL	67.6	70.1	72.3	73.8	74.8	76.5	77.0	77.3
Orient. (165º)	LL	83.8	81.6	78.8	77.3	73.8	73.2	73.0	72.7	LL	67.6	70.9	73.6	74.2	75.1	75.3	75.8	75.9
	C	85.0	82.7	78.4	75.6	74.4	72.6	71.0	70.8	C	66.4	70.1	72.8	74.5	75.0	75.7	76.1	76.3
	RL	83.1	79.0	73.8	72.4	71.5	71.3	71.5	70.8	RL	69.8	71.5	74.3	74.3	75.2	75.8	77.0	76.9

Fig. 7 Frequency distribution of annual HS and CS within different UCCs, and canyon RPs in association to each orientation with an hourly resolution associated to the DP_2 between the years 2008–2020 through the adapted human thermophysiological thresholds

As demonstrated in Fig. 8(B), it was possible to correlate daily maximum and minimum PET_I values during December and January against outdoor values. Irrespective of the notable variation of outdoor values, particularly in January, PET_I minimums and maximums remained stable, together predominantly oscillating ~ 24 °C.

Between both the summer and winter comparisons, and to further highlight the disparity of human thermophysiological conditions for both contexts, both seasons were included in both assessments. Overall, the range of outdoor environmental conditions in Ankara was considerable, with PET_O values ranged between − 21.6 and 48.0 °C for the same year, equating to a substantial annual PET_O deviation of ≤ 69.6 K.

4 Discussion

Encompassingly, within this research, the objective of the study was to detect and quantify yearly and seasonal human thermophysiological vulnerability within a capital city that has witnessed very little bioclimatic assessment. Ankara also continues to observe rapid and unregulated

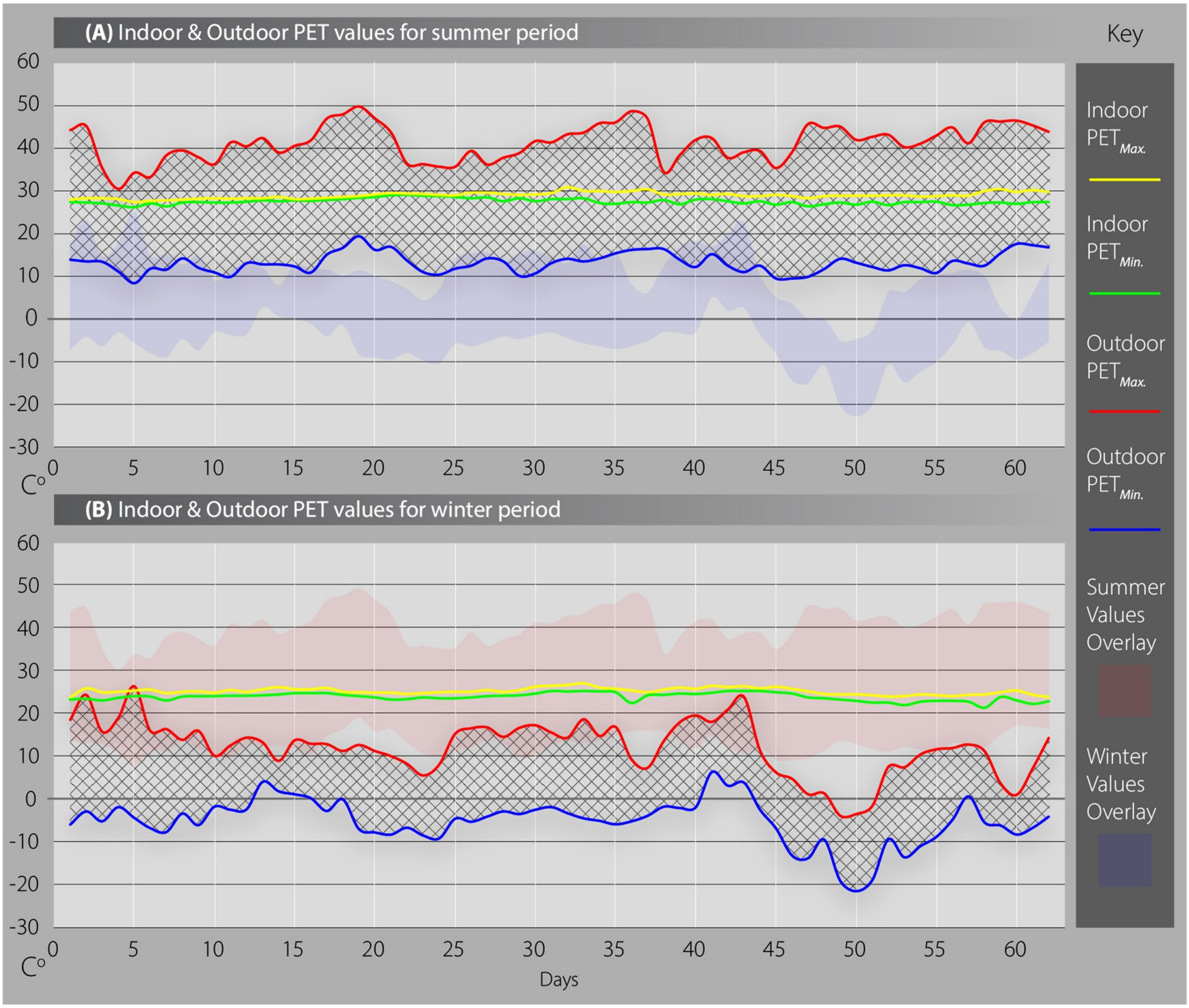


Fig. 8 Correlation between minimum and maximum PET_I and PET_O values for both the summer season (i.e. July–August of 2020) (A) and winter season (i.e. December–January of 2020/21) (B) using data processed from the local AMS, and the in situ indoor KHS station

densification patterns with still a significant prevalence of out-dated and vulnerable residential construction methodologies. Moreover, the research also contributes to the existing literature given its approach of a case study that is exposed to both significant levels of annual heat and cold stress. The 'human-centred approach' led to an identification of (i) how the further development of existing methodologies, including the approach towards UCCs, their inner RPs, and annual solstice dynamics, further refined means to quantify increasing thermal risk factors, in situ; and (ii) how the interchange and translation from top-down into bottom-up assessments at different scales through the use of an EBM thermal index can raise a better awareness and interdisciplinary bridging which can aid professionals that are challenged with developing thermal-sensitive means to shape contemporary urban fabrics, including urban planners, designers, and architects. As to be expected, such efforts merge with those associated to the growing climate change adaptation agenda, where urban human well-being and safety has never been as jeopardised. The findings produced clear bioclimatic perspectives into the need to go beyond just considering aspects ratios, and just as importantly, recognise the significant role of orientation, thermal stress type, and furthermore, the areas within the urban canyons themselves that can host drastically divergent frequencies in human thermophysiological stress exposure.

4.1 Extrapolation of thermophysiological urban conditions between scales from urban to in situ

The FDD of human thermophysiological thresholds for Ankara's urban centre over the past decade revealed both the frequency and distribution of annual/seasonal CS and HS. Similar in nature to the results presented by Nouri et al. (2021) for Ankara, although set to different hours, it became immediately clear that the initial thresholds as presented by Matzarakis et al. (1999) required expansion, particularly to account for CS, as also undertaken by Bauche et al. (2013) and Matzarakis (2014). The coldest nocturnal hour (05:00) during the late autumn and early spring predominantly varied between CS5 and CS6, with some noteworthy frequency during the hottest diurnal hour (15:00) during the winter as well. Conducive with previous studies, including for Asian (e.g. Yang and Matzarakis 2016), European (e.g. Nouri et al. 2018a), and Australian (e.g. Djamila and Yong 2016) geographic/climatic contexts, such approaches complement important information provided by top-down KGC system to better understand environmental impact upon the human biometeorological system.

Cross examining such environmental conditions against morphological considerations took this bottom-up 'human-centred approach' understanding to a considerably finer detail. This was possible through the processing of hourly data for all months between the years of 2008 and 2020, within Ankara's common morphological framework. While some studies have utilised FDD analysis of particular human thermophysiological thresholds (e.g. Ketterer and Matzarakis 2014; Matzarakis et al. 2018b), this study conducted a novel methodology to downscale the enhanced comprehension of CS, NTS_{EXP}, and HS exposure. This was because of two predominant reasons. Firstly, and given the high disparity of environmental conditions within the same respective canyon as identified by a limited number of studies for symmetrical canyons (e.g. Nouri et al. 2017; Rodríguez-Algeciras et al. 2021; Rodríguez Algeciras et al. 2016) and a-symmetrical canyons (Qaid and Ossen 2015; Rodríguez-Algeciras et al. 2017), the study established three independent RPs within an UCC evaluation. Secondly, the study proposed a new approach to break down the analysis into both yearly and seasonal human CS, NTS_{EXP}, and HS exposure.

For the case of Ankara, the results of this analysis presented considerably further comprehension of the in situ impacts pertaining to common urban morphological characteristics in the city centre. More specifically, this included far greater insight into the crucial significance of radiation fluxes in better approaching local urban human environmental conditions (Abreu-Harbich et al. 2013; Herrmann and Matzarakis 2012). Such attributes are moreover those that fall easily within the scope of urban bioclimatic management and planning assessment efforts to improve human thermal conditions within consolidated fabrics (Alcoforado et al. 2009; Alcoforado and Matzarakis 2010; Martin and Paneque 2022; Matzarakis et al. 2018b; Nouri and Matzarakis 2019).

4.2 Identification of annual/seasonal frequency distribution of urban human in situ heat/cold vulnerability

4.2.1 Annual joint distribution of thermophysiological thresholds

It was fundamental to remember that within this study, two groups of UCCs were investigated, i.e. those that (i) were commonly found within Ankara's existing urban fabric, i.e. $UCC_{0.25}$ through to $UCC_{2.00}$; and secondly, (ii) depicted upon scenarios analogous with scenarios of urban densification patterns within its existing fabric, i.e. $UCC_{2.50}$ through to $UCC_{3.50}$. For this reason, while climate change impacts were not considered in this study, the implications of the continued rapidly and unregulated densification of the Turkish capital city (Çalışkan and Türkoğlu 2014; Karaca et al. 1995; Nouri et al. 2022a; Yuksel and Yilmaz 2008) could also be considered.

For the annual analysis, within the DP_I, it was possible to determine that the frequency of NTS_{EXP} remained ~ 48% (767 min), CS ~ 26% (416 min), and a similar HS frequency of ~ 28% (448 min). These frequencies naturally varied according to the UCC's AR, which in comparison to $UCC_{3.50}$, led to increases in CS frequency by up to 4.5% (72 min), and a decrease of HS frequency by up to 7.1% (114 min).

In terms of urban morphology, beyond the predictable changes associated to AR composition, the reason for such changes between the UCCs is attributable to two attributes, the (i) orientation of the canyon; and (ii) location of the RPs within the respective canyon. Both two morphological aspects have a symbiotic relationship with radiation fluxes because of the encompassing solstice pattern, and how many hours a respective in situ location is exposed to solar radiation. This variable proved to be a far more crucial variable to assess human thermophysiological stress within Ankara's urban city centre. Such a result is concomitant with previous international studies, from different climatic contexts, that irrespectively identified the higher influence of radiation within different morphological settings in comparison to the sole use of Ta_O to assess human thermal comfort thresholds (e.g. Ali-Toudert and Mayer 2006; Herrmann and Matzarakis 2012; Ketterer and Matzarakis 2014; Nouri et al. 2017; Santamouris et al. 1999).

Amid all twelve orientations and RPs, the most significant outputs from the yearly DP_I analysis were the general frequency distribution of CS, NTS_{EXP}, and HS in Ankara. It was revealed that while its KGC may be grouped within a 'Snow/Cold Climate', its hot and dry summers led to an equal distribution of annual environmental heat and cold vulnerability within its consolidated urban fabric. This was an important result given that the limited amount of studies which investigated thermal comfort through the use of EBM indices in the Turkish capital (e.g. Çalışkan and Türkoğlu 2014; Nouri et al. 2021, 2022b; Türkoğlu et al. 2012) has yet to consider the crucial effects of urban morphology upon human thermophysiological in situ risk detection and quantification.

4.2.2 Seasonal frequency of diurnal HS during the summer

With regard to the analysis undertaken for DP_2, both the summer and winter periods were individually investigated. Such an approach enabled a finer understanding of environmental conditions conducive to environmental CS and HS, in particular the scenarios and areas representative of urban human thermophysiological risk in Ankara.

The RP analysis in this section was in alignment with the results obtained from a proceeding study within the case of Lisbon (with similar latitude with that of Ankara). More specifically, based upon the use of modified PET (mPET) (Chen and Matzarakis 2017), and the methodology by Charalampopoulos et al. (2016) to determine in situ thermal load (i.e. PETL), the study determined the priority levels of urban Thermal Attenuation Priority (TAP) (Nouri et al. 2017). Respectively, based on the two assessed orientations (North-to-South and East-to-West), the western area (corresponding to $RP_{LL}OR_0$ in this study) of the North-to-South canyon and the southern area (corresponding to $RP_{LL}OR_{90}$ in this study) of the West-to-East canyon revealed to be the areas with the lowest TAP levels. When reviewing the results as presented in Fig. 7, it was possible to strongly correlate the generally lower in situ HS frequency within both $RP_{LL}OR_0$ and $RP_{LL}OR_{90}$ for all UCCs, including in the case of $UCC_{0.50}$.

These outcomes indicated that similar interdisciplinary bottom-up approaches can be applied to the case of Ankara. More specifically, through the produced detection and quantification of urban human thermophysiological thresholds, it was possible to determine numerous key outcomes that can be met with bioclimatic thermal-sensitive urban design and planning perspectives and management.

Overall, in the case of HS during the summer months, given its higher exposure to radiation fluxes, it was possible to identify that Ankara's existing fabric ($UCC_{0.25}$ through to $UCC_{2.00}$) revealed the highest exposure to HS conditions. $UCC_{0.25}$ revealed a HS frequency of up to 85% (3060 min), closely followed by $UCC_{0.50}$. Both UCCs were contexts where in situ bioclimatic conditions presented very high frequencies of HS within all RPs, with the exclusion of $UCC_{0.50}RP_{LL}OR_0$ through to $UCC_{0.50}RP_{LL}OR_{90}$ with frequency drops of up to 6.7% (241 min) within the same canyon. This suggested the high importance of addressing such high HS frequency, for any UCC of this morphological typology, independent of its orientation, and RP within the canyon.

$UCC_{1.00}$ and $UCC_{1.50}$ represented morphological settings where RP_C and RP_{RL} continued to characterise areas of higher HS frequency within most orientations, except for those with an orientation of $\geq 135°$. More prominently, and in comparison, to the previous point, such outcomes were already indications of where potential thermal-sensitive design measures could be prioritised in such UCCs.

In alignment with other international case studies, HS frequency reduction pattern between the UCCs with orientations between 105 and 135° was lower and thus resulted in HS remaining higher even within $UCC_{3.00}$ and $UCC_{3.50}$. For this reason, given the high exposure to radiation fluxes because of the summer solstice, these canyons orientations represented the cases that were generally the most susceptible to HS in all eight ARs. Such outcomes were relatively concurrent with previous studies that identified that East-to-West orientations were generally those more susceptible to higher HS frequencies (e.g. Ali-Toudert and Mayer 2006; Johansson and Emmanuel 2006; Ketterer and Matzarakis 2014; Rodríguez-Algeciras et al. 2017; Rodríguez Algeciras et al. 2016). The slight divergence in orientation beyond 90° can be attributable to two methodical factors, the use of the DP_2 rather than the reference to individual hours, and secondly, to the continual integration of solstice modification throughout the three summer months.

Lastly, UCCs with orientations between 45 and 90° were the contexts in which HS frequency dropped the strongest between the eight ARs, with resulting $UCC_{3.50}$ presenting HS frequencies of 69.5% (2502 min). It was still worth noting that within such orientations, RP_{RL} always was the area within the canyons which consistently revealed the highest exposure to HS throughout the different ARs during the hottest hours of the day. As exemplified by $UCC_{2.00}RP_{RL}OR_{75}$, it was meaningful to recognise that the 5.5% divergence in comparison to the other two RPs represented a total of 198 min of extra HS conditions, within the same canyon, with a width of 20 m. Within an interdisciplinary perspective, in addition to those already mentioned, such a scenario would be another promising opportunity for in situ thermal-sensitive design approaches, even if based upon an ephemeral nature to reduce radiation fluxes at the pedestrian level as presented by, e.g., Kántor et al. (2018), Nouri et al. (2018a), and Nouri and Costa (2017a).

4.2.3 Seasonal frequency of diurnal CS during the winter

The CS assessment during DP_2 for the winter months revealed that cold conditions varied less between the eight ARs, particularly for specific areas of the UCCs. This was prominently the case for the RP_{LL} region within most UCCs, where CS frequency was frequently at ~ 74% (2664 min) in $UCC_{0.25}$. For orientations between 30 and 120°, $UCC_{0.25}$ and $UCC_{0.50}$ revealed some differences in CS frequency between the RPs; however, this was no longer the case for the ARs. More encompassingly, within such orientations, CS increased less than 1% between $UCC_{1.00}$ and $UCC_{3.50}$. Such can be directly attributable to the lack of radiation exposure/variation provided by the winter solstice.

UCC orientations between 150–165° and 0–15° revealed considerable differences in CS frequency. CS incidence levels were generally lower in $UCC_{1.00}$ through to $UCC_{3.50}$, with increased differences between the RPs. This meant that these orientations represented those with less overall CS exposure. These were also contexts in which $UCC_{0.25}$ and $UCC_{0.50}$ revealed the lowest CS frequencies of 66.2% (2376 min) and 69.2% (2484 min), respectively.

Pertaining to the CS results in this study, it was possible to identify that CS was encompassingly less variable than HS amongst the different morphological settings. Although within an even colder climate, the Russian study in Birobidzhan undertaken by Bauche et al. (2013) revealed similar relationships between CS and HS, whereby the reduction of radiation fluxes during the summer had clearer effects on human thermophysiological stress, rather than finding means to augment them in contexts with high urban density.

Following this train of thought and returning to the 'human-centred approach', numerous outcomes related to bioclimatic thermal-sensitive urban design and planning perspectives related to CS management could be established. Firstly, in alignment with the aforementioned study, and concomitant with canyon orientation studies upon the distribution of human thermophysiological thresholds undertaken by Ketterer and Matzarakis (2014), when approaching annual CS, it was determined that permitting exposure to radiation fluxes was crucial during the winter, when/where possible. While the study did not include RP specification within its analysis, the same valuable conclusions were determined within other studies that also looked at ensuring winter radiation fluxes. Within the study conducted by Nouri et al. (2018b), different morphological ARs in Lisbon were assessed in terms of the impact of the *Tipuana tipu* species had upon local thermal comfort conditions during the summer and winter periods, including within different RPs. Affiliated with the conclusions drawn from the study, it became paramount to verify that the reductions of radiation during the summer because of the tree crown would not render thermal discomfort during the winter where such radiation patterns would be desired.

For this reason, it become paramount to ensure that, when possible, in the case of $UCC_{0.25}$ and $UCC_{0.50}$ and general orientations (i.e. between 150–165° and 0–15°), any bioclimatic thermal-sensitive urban design and planning approach, including those considered for the summer, must be weighed carefully in terms of their interaction with radiation fluxes during the winter. As shown in Fig. 7, the interaction between three factors (i.e. the low winter solstice, DP_2, and edification) as initially represented in Appendix Figures 9 and 10 depicts the clear relationship between CS frequencies and the green highlighted hours within the DP_2.

4.3 Identification of outdoor conditions with representative indoor conditions for winter/summer seasons

The international community has identified that, within an era of climate change and rapid urban densification, there is an urgent need to consider in situ indoor conditions that supplement measurements from local MSs to better understand indoor HS thresholds and risk factors (Basu and Samet 2002; Nazaroff 2008; White-Newsome et al. 2012). Within the case of Ankara, a similar urgency has been highlighted regarding the cause-and-effect synergy between indoor and outdoor human thermal risk factors. Particularly, given its vulnerability to heatwaves hosted within hot summers (Demirtaş, 2018), and encompassing augmentations of general HS risk as a result of climate change (IPCC 2013; Matzarakis 2016, 2022; Ozturk et al. 2015).

During the summer period, new locally defined Extreme Heat Event (EHEs) were defined for the capital and subsequently correlated to interior measurements within a representative vulnerable residential construction typology. Two distinct relevant approaches were conducted: the (1) initial study focused upon erection of the local EHEs, and then assess their impact upon a new Indoor Cooling Degree Necessity (ICDN) metric based upon Ta as detailed in Nouri et al. (2022a); and (2) follow-up study, that instead of using Ta and the ICDN metric, utilised the PET and their associated PS levels to further assess the impact of a combination of different variables upon the human biometeorological system during different summer heat events (Nouri et al. 2022b).

Within this study, the same vulnerable and naturally ventilated residential construction typology was utilised to determine PET during the months of July and August 2020, but moreover, during the winter months of December and January 2020/2021. In this way, both CS and HS levels could be determined against outdoor conditions during the different seasons with substantially divergent climatic conditions. During the summer season, PET_I remained constantly close to 30 °C, particularly when maximum PET_O exceeded 40 °C and minimum PET_O remained above 15 °C. In alignment with previous studies, these results indicated that such naturally ventilated residential dwellings incessantly presented conditions equating to HS conditions, with PS thresholds reaching Moderate HS levels (i.e. of HS2). While of course lower than diurnal outdoor conditions, the significance of these results was less to do with exposure to higher HS grades, and more to do with the exposure to lower, yet incessant HS within the homes of the urban inhabitants. Such an outcome revalidates the early, yet still continuously resonating, results presented by Hebbert and Webb (2007), pertaining to the crucial management of lower extreme, yet incessant, thermal risk factors that are symbiotic to urban climate, and subsequently, to the human biometeorological system as well (Matzarakis 2021).

Such outcomes moreover relayed to the risks highlighted by Nouri and Matzarakis (2019) whereby periods of extended human thermophysiological stress (i) shall not only affect the peripatetic transitioning between indoor and outdoor movement patterns/durations, but in addition, the individual psychological aspects that catalyse such human behaviour; (ii) imply that 'past experience' (e.g. being outdoors during a local EHE) of thermal discomfort shall increase the 'expectation' to address cumulative discomfort in a setting ideally favourable towards environmental NTS conditions; and lastly, (iii) limit the ability of cumulative diurnal thermal loads to fluctuate adequately to permit the human biometeorological system to regulate, replenish, and restore attributes of human physiology that are crucial to the circadian rhythm cycle, and different sleep stages. With regard to HS and resulting sleep disorders, also using the PET index, Nastos and Matzarakis (2008) identified that extended periods of extended diurnal and nocturnal HS in Greece resulted in substantial increases in sleeping disorders, which moreover did not seem to placate or adapt to the respective climatic conditions. In alignment with the disclosed approaches and studies which cross-reference the evaluation of thermal indices such as PET and human thermal behaviour, even more recent studies continue to endorse such relationships, including in more oasis and arid-based climatic contexts (e.g. as discussed in Berkouk et al. 2022; Matallah et al. 2021).

When considering the winter season, the KHS stations revealed that indoor PET values were almost always within the NTS and NTS_{EXP} thresholds. Furthermore, it was possible to determine that, on average, winter PET indoor values were around 4 °C cooler than those presented for the summer. Of course, there was a very significant distinction between these two settings. During the summer, the indoor environment is cooled through natural ventilation, and on the other hand, central heating was utilised during the winter. For this reason, although this study addressed a particularly unexplored topic pertaining to the symbiotic relationship between indoor-outdoor human thermophysiological relationships using an EBM index, including with regard to CS during the winter, it must be remembered that the resulting indoor in situ conditions were associated to environmentally controlled/conditioned settings in the winter.

On this matter, this presented the opportunity for a future study to further focus specifically on winter conditions. Such research could investigate issues such as energy consumption to examine the requirements to maintain such indoor temperatures within frequent residential units found in Ankara, whose buildings shells have particularly high thermal transmissivity values (i.e. with U-values reaching 1.7 W/m^2K). The study could moreover identify energy requirements and costs to maintain indoor conditions, which as identified by mid-January 2021 in this existing study, struggled to maintain the same indoor temperatures when outdoor minimum PET reached − 21.6 °C and maximum PET also dropped to − 4 °C.

Meanwhile, the recognised differences between summer and winter indoor in situ conditions were an important outcome in the context of the disclosed divergences in annual human thermophysiological conditions. Such outcomes were further emphasised in light of the still highly common construction typologies that do not yet meet current building standards within Türkiye's second largest city, and capital (Esiyok 2006; Gültekin and Farahbakhsh 2016; Nouri et al. 2022a).

4.4 Reflecting results upon Sustainable Development Goals in Türkiye

Encompassingly, when approaching initial SDGs for Türkiye, the term 'sustainable', should by its very definition, goes beyond solely facilitating the link between urban thermal comfort and air quality management, including in the case of user satisfaction in dwellings (Afacan and Demirkan 2016). Thermal comfort can also be approached through a wider socio-economic perspective, in which scientists must moreover consider factors associated to respecting, protecting, and fulfilling human right standards (Möstl 2020). Developed countries are working with human rights to provide better health and well-being which is the main aim of the third goal (i.e. 'SDG3: Good health and wellbeing') and the eleventh goal (i.e. 'SDG11: Sustainable cities and communities'). With regard to all 17 SDGs, local governments should follow an integrated approach to deal with human thermophysiological thresholds in light local HS and CS vulnerabilities (both from a practical and a legal point of view).

A detailed assessment of this was undertaken by Yang and Matzarakis (2019) for China, who underlined further comprehensive associations with human thermophysiological thresholds, including with (i) 'SDG1: No poverty' – by building resilience within thermally vulnerable conditions, including against EHEs; (ii) 'SDG3: Good health and wellbeing' – associating thermal risk factors to excess urban mortality and morbidity rates, particularly within vulnerable age/health groups; (iii) 'SDG11: Sustainable cities and communities' – relating local thermal risk factors both to low frequency yet high impact disasters, and moreover, the high frequency but lower impact disasters associated to the adverse environmental impact of cities; and also means to improve risk management, and overall thermal resilience to disasters through climatic adaptation and mitigation; and, lastly (iv) 'SDG13: Climate action' – ensuring climatic-related hazards are also approached in terms of their impacts upon the human biometeorological system and thresholds.

Following this reasoning, both human rights and SDGs symbiotically share common ground to ensure and enhance long-term quality of life standards, comfort, safety, and the overall well-being of individuals, including urban inhabitants. Regarding the latter, the challenge is that the contemporary and consolidated urban fabric lacks common and systematised frameworks (Meier et al. 2017). Based on this rational, within the encircling stance of the SDGs, there needs to be, not only the implementation of human rights towards thermal comfort, but moreover, the on-going task of present/future monitoring of thermal risk standards, methodologies, and examples of good practice. By association, such efforts must continue to re-energise predominantly stagnant SDGs in Türkiye, including that of 'SDG13: Climate action' (UNSDCF 2021).

As a result, and with a focus upon the detection and quantification of yearly/seasonal CS and HS levels through a 'human-centred approach', this study utilised the case of Ankara to demonstrate how (1) in situ urban morphological characteristics of a rapidly densifying city with limited building and planning regulations (Karaca et al. 1995; Nouri et al. 2022a; Türkoğlu et al. 2012; Yuksel and Yilmaz 2008) could be assessed in terms of thermal risk detection and quantification; (2) scale interchangeability between top-down approaches (e.g. KGC system), and how different bottom-up scaled approaches can produce finer understanding of local in situ risk factors upon the human biometeorological system (Nouri et al. 2018a; Yang and Matzarakis 2016); (3) the distinction between different areas within the same UCC can provide different bioclimatic conditions, during both the entire year, and moreover for the summer and winter seasons; (4) a common yet vulnerable residential construction typology revealed to what extent outdoor conditions influence indoor in situ environmental conditions during Ankara's cold/snowy winters and hot/dry summers; and lastly, (5) the future morphology associated to urban densification patterns in Ankara can influence already existing conditions as predominantly represented by $UCC_{0.25}$ through to $UCC_{2.00}$.

4.5 Study limitations

As this research was focused firstly upon the methods of detection and quantification of human thermophysiological thresholds, the specific mapping of the UCCs was not undertaken. Given scope and objective of this research, including the use of new methodical approaches, the study was predominantly focused upon both detection and quantification of HS and CS risk throughout the year based upon 12 years of hourly data. However, a following study is already being prepared to map all the UCCs within Ankara's districts, both in terms of their orientation and AR. Such an approach shall thus link and pinpoint the human thermophysiological risk factors with specific areas of Ankara containing the specified morphological characteristics.

While this study does evaluate morphological compositions that are associated to potential future urban densification patterns, future aggravations specifically associated to climate change impacts are not considered within this study. Nevertheless, these projections are currently being processed for the specific case of Ankara through the use of Representative Concentration Pathway (RCP) scenarios by the mid and end of the twenty-first century. These projections are being undertaken both in terms Ta and PET, for both the $RCP_{4.5}$ and $RCP_{8.5}$ scenarios.

In addition to general urban thermophysiological thresholds pertaining to both CS and HS, and the representative indoor evaluation that characterised frequent yet vulnerable residential construction methodologies, 864 outdoor morphological settings were assessed against 12 years of hourly data. These settings were moreover assessed through three different means, one representing annual (via DP_1), and another two representing the winter and summer seasons (via DP_2). This rendered a total of 2592 scenarios that were based upon two groups of UCCs, namely, those that (i) were commonly found within Ankara's existing urban fabric, i.e. $UCC_{0.25}$ through to $UCC_{2.00}$; and secondly, (ii) depict upon morphological results associated to the scenarios of urban densification patterns, i.e. $UCC_{2.50}$ through to $UCC_{3.50}$.

Given the already considerable different in situ assessments within the study, although important, other less frequent types of UCCs were not considered. More specifically, while this study focussed on symmetrical canyons given their predominance within the existing framework, a future study that would consider a-symmetrical could also be conducted to complement the results of this study.

Finally, and concomitant to the first two limitations of this study that are already being addressed in a subsequent study, while this research has focused upon HS and CS risk identification based upon intrinsic urban morphological characteristics, such a risk assessment opens the opportunity to subsequently propose more detailed thermal-sensitive planning guidelines and design proposals. These include, but are not limited to, urban green and blue infrastructure solutions that will address both existing and future human thermophysiological risk factors because of climate change scenarios until the end of the century.

5 Concluding remarks

This research was focused upon means in which to detect and quantify yearly and seasonal human thermophysiological risks within the urban consolidated fabric of Ankara. Equipoised upon the 'human-centred approach', the outputs of the study revealed two principal outcomes: (1) how existing and new assessment methodologies can be utilised to approach both significant levels of outdoor/indoor cold and heat stress, and moreover, reflect such quantitative risk factors upon the human biometeorological system through the use of an energy based model index; and (2) transition from top-down assessments (based upon temperature and aridity) to bottom-up assessments undertaken at different scales through the use thermal indices such as the physiologically equivalent temperature. Pertaining to the latter, such an approach allowed for the identification of both general urban human thermophysiological conditions in Ankara, and subsequently, how common in situ morphological settings permitted a finer understanding of these conditions in characteristic urban canyons, and furthermore, within the different areas of the canyons themselves.

These conclusions salient the need to go beyond considering just the changes in aspect ratios, and just as crucially, recognise the significant role of orientation, thermal stress type, and in addition the areas within the urban canyons themselves. The disclosed results produce clear bioclimatic perspectives into (i) which orientations present the highest incremental divergence between the eight aspect ratios; (ii) which type of environmental stress is most often associated and/or predominant to the different urban morphological characteristics; and (iii) where the local in situ thermal-sensitive and planning measures can be considered within the canyons based upon other crucial factors, in addition to the urban aspect ratio.

Encompassingly, in terms of heat stress during the summer period, given its elevated exposure to radiation fluxes, it was possible to identify that Ankara's existing fabric revealed the highest exposure to heat stress conditions. It was possible to determine that urban canyon cases with the highest heat stress frequency during the summer were orientations between 105 and 135°. Within these canyons, including those with an aspect ratio of 3.50, the frequency of heat stress almost always remained above 72% (2592 min). Such a result revealed that lower aspect ratios could still present lower heat stress frequencies than those obtained from higher aspect ratios. In addition, the results in this study highlighted the equally significant factor of the areas within the canyon themselves when approaching thermal risk detection and quantification.

When approaching cold stress, it was possible to conclude that cold stress was encompassingly less variable than heat stress amongst the different morphological settings. Nevertheless, urban canyons with orientations between 150–165° and 0–15° revealed considerable differences in cold stress frequency. Incidence levels remained lower in aspect ratios 1.00 through to 3.50, with increased differences between the sub-areas within the canyons themselves. Such a result concluded that these orientations and respective areas represented those with less overall cold stress exposure.

For this reason, it become paramount to ensure that, when possible, in the case of the lowest aspect ratios, and general orientations (i.e. between 150–165° and 0–15°), any bioclimatic thermal-sensitive urban design and planning approach, including those considered for the summer, must be weighed carefully in terms of their interaction with radiation fluxes during the winter. This being said, and because of the divergent annual solstice, such a consideration became more important given that the orientations with the lower cold stress frequencies had a restricted connection with those presenting higher heat stress frequencies.

Pertaining to the indoor results in this study, depicting upon a typically naturally ventilated vulnerable residential dwelling with out-dated construction methods, both cold and heat stress levels were determined against divergent annual outdoor conditions (with 2020/2021 revealing a substantial annual outdoor physiologically equivalent temperature deviation of ≤ 69.6 K). During the summer season, the indoor physiologically equivalent temperature remained constantly close to 30 °C, particularly when maximum outdoor physiologically equivalent temperature exceeded 40 °C. However, during the winter season, indoor measurements revealed that indoor physiologically equivalent temperature values were always conducive of no thermal stress thresholds given the continuously activated central heating system. Such indoor temperatures could not be maintained during periods in which outdoor minimum physiologically equivalent temperatures reached − 21.6 °C and maximum values remained at − 4 °C.

Including when considering the various emerging relevant Sustainable Development Goals for Türkiye with regard to thermal comfort attributes, action needs to be undertaken to further improve the overall climatic resilience of cities such as Ankara. However, intrinsic to the implementation of concrete thermal-sensitive responses via bottom-up adaptation efforts which present means to ensure urban living standards, well-being, and safety in an era of climate change is the preceding requirement to understand the risk that such measures are intended to address.

As demonstrated by the outputs of this study, the approach of both yearly and different seasonal scopes permitted a better comprehension of the symbiotic relationship of existing/future urban morphological settings with paramount risks for the human biometeorological system. Such an approach allowed for different climatic variables to be considered, including the fundamental role of in situ dynamic radiation fluxes that were indubitably dictated by encompassing yearly/seasonal solstice patterns. It is believed that this interdisciplinary know-how between human biometeorology and urban planning sets the path for two types of urgent approaches within cities such as Ankara, these being (1) the technical foundation to determine thermal-sensitive architectural, planning, and bioclimatic design measures (e.g. but not limited to green and blue infrastructure) when attenuating such risk factors in the medium-to-long-term; and just as importantly, (2) the chance to better map and manage environmental risk within the urban fabric in the shorter term while adaptation measures are being considered, financed, and implemented in the longer term. In such a way, already consolidated urban fabrics can be re-approached, both in terms of its indoor and outdoor contexts, to provide solutions associated to different interconnected timeframes to ensure the sustainable longevity, and quality, of urban inhabitants within an era prone to further climatic aggravations.

Appendix

Table 5 Specifications of Kestrel Heat Stress (KHS) 5400 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	− 29.0 to 60.0 °C

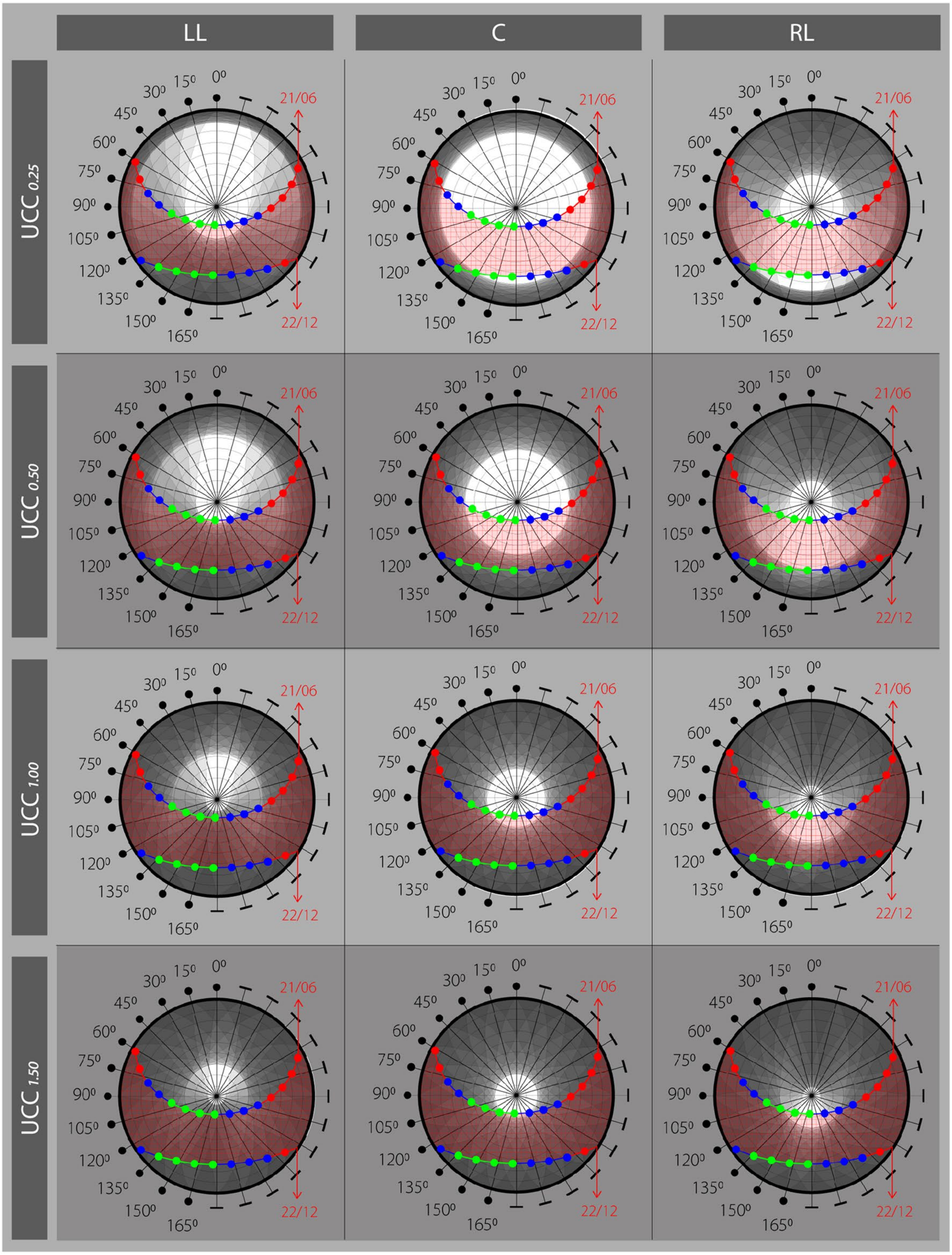


Fig. 9 Illustration of SVF overlay for the different Reference Points (RPs) between $H/W_{0.25}$ and $H/W_{1.50}$ for each Urban Canyon Case (UCC) amongst the twelve orientations with relationship with to solar radiation between the winter and summer Solstice patterns for Ankara

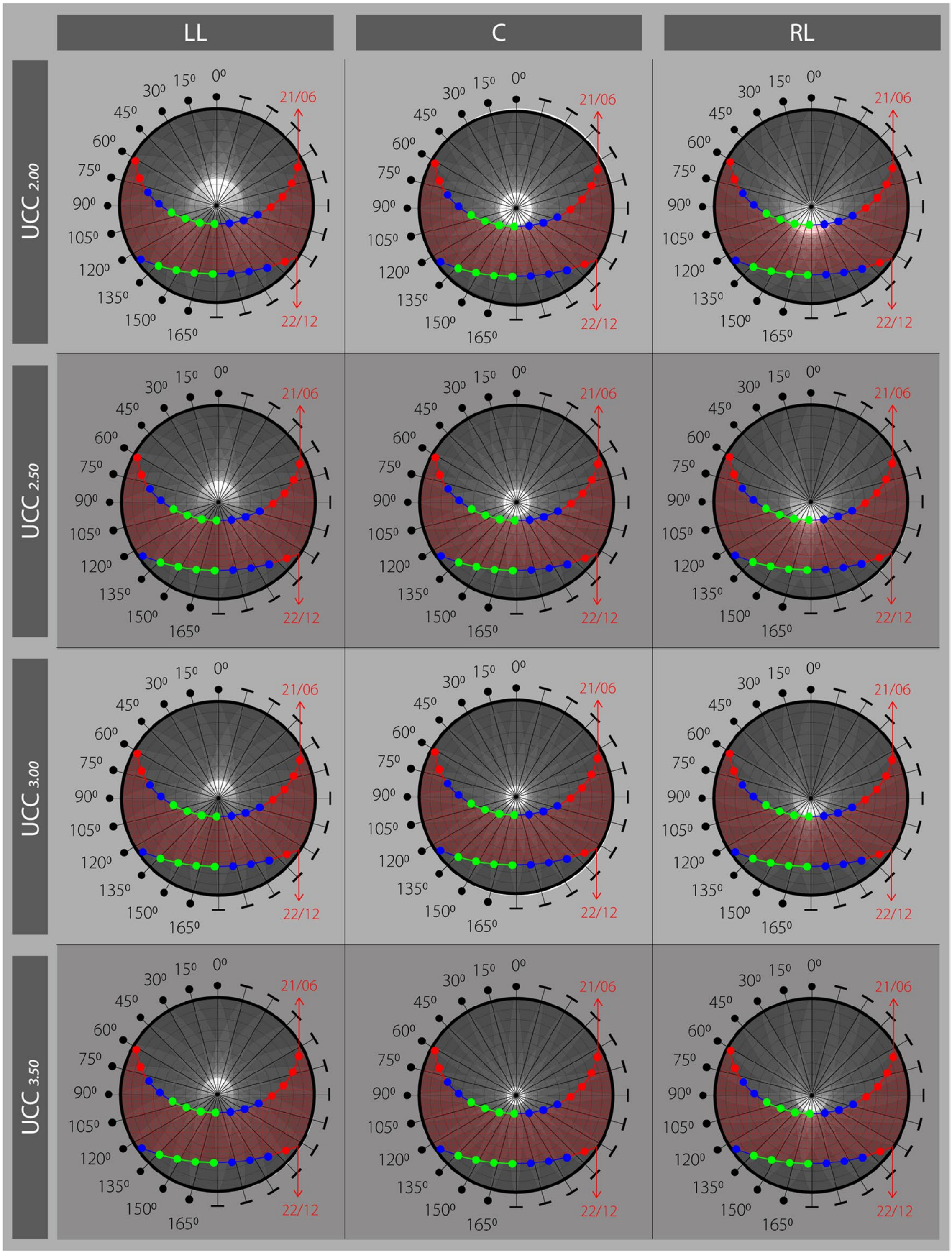


Fig. 10 Illustration of SVF overlay for the different Reference Points (RPs) between H/W$_{2.00}$ and H/W$_{3.50}$ for each Urban Canyon Case (UCC) amongst the twelve orientations with relationship with to solar radiation between the winter and summer Solstice patterns for Ankara

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Data availability The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

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Declarations

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