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Investigating the Relationship of Outdoor Heat Stress upon Indoor Thermal Comfort and Qualitative Sleep Evaluation: The Case of Ankara

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Abstract: The necessity of exploring the relationship between sleep quality and the thermal environment has amplified regarding increasing heat stress risk on the human body due to climate change, particularly in vulnerable uninsulated buildings in Ankara. Within this scope, this study investigated occupants' sleep quality and human thermal comfort in insulated and uninsulated buildings under three local extreme heat event thresholds: (1) typical summer days (TSD_{25}), (2) very hot days (VHD_{33}), and lastly, (3) heat wave events (HWE_{31}). Within a two-tiered approach to thermal comfort evaluations, the human thermal comfort of occupants was identified through the calculation of physiologically equivalent temperature (PET) from the climatic data of local meteorological stations. The psychological thermal comfort and sleep quality of participants were evaluated by questionnaires during each heat event. The results of this study demonstrated that the physiological thermal load of the participants was highest during VHD_{33}s, given that both outdoor and indoor PET values presented their highest values within VHD_{33} events. Furthermore, the outdoor PET values reached extreme heat stress based on physiological stress grades with 43.5 °C, which indicated the exacerbated vulnerability of Ankara during extreme heat events. The PET values were consistently higher in uninsulated buildings than in insulated buildings. Also, most of the mean psychological thermal comfort votes and sleep quality votes were better in uninsulated buildings than in insulated ones during TSD_{25}s and HWE_{31}s, while it was the opposite within extreme conditions of VHD_{33}s. The outputs of this study contribute to interdisciplinary efforts to attenuate the existing and impending risks of climate change on human life by defining the influence of increasing outdoor heat stress on indoor spaces, thermal comfort, and the sleep quality of occupants.

Keywords: thermal comfort; sleep quality; PET; outdoor heat stress; extreme heat thresholds; Ankara

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1. Introduction

Sleep quality, which refers to the assessment of an individual's psychological and physiological well-being experienced during sleep, plays an integral role in human life [1,2]. At its core, psychologically, it is determined by the deepness and calmness of sleep, while its physiological dimensions are defined by factors such as total time, delay, and the number of awakenings during sleep [3,4].

The human body utilizes sleep to recover from the effects of daily mental and physical stresses. For instance, sleep restores the strength of the human body to sustain daily routines. Therefore, sleep quality has a considerable interrelation between the physiological and psychological health of humans. Cognitive performance, immunity, metabolism, and mental health are impaired by poor sleep quality [1,5–7].

The human body uses the circadian rhythm of core body temperature (T_{cr}) to regulate sleep. To prepare for sleep, the body decreases the T_{cr} by sending warm blood from the body core to the skin. Warmblood transfers its heat to the skin and causes an increase in the skin temperature (T_{sk}). At the skin, the body loses its heat and initiates sleep [5,8–12]. Since the net heat loss of the body is affected by many indoor climatic factors, it is crucial to provide an optimal indoor thermal environment to improve sleep quality [2,13,14].

In the literature, many studies have been conducted to examine the impact of indoor thermal parameters on sleep. For instance, Haskell et al. [15] studied the effects of high and low T_a on human sleep stages and found lower rapid eye movement (REM) sleep, the last sleep stage when the human thermoregulatory system impairs [16], and higher wakefulness at 37 °C compared to 29 °C. Similar findings were also reported by [17], who investigated the effect of humid heat on human sleep stages. The results demonstrated a considerable decrease in REM and stage 3 sleep at 35 °C T_a with 75% RH compared to the indoor conditions with 29 °C T_a and 50% RH. In the study by [6], a 29 °C pre-sleep environment provided longer REM and stage 3 sleep compared with those with 23 °C and 26 °C Ta. In addition to studies focused on sleep stages, the influence of T_a on overall sleep quality was also investigated by many researchers. In a study based on both subjective and physiological measurements, [18] suggested that T_a substantially affects sleep quality. [19] revealed lower sleep onset latency, higher slow-wave sleep, and higher subjective sleep quality in a 30 °C sleep environment than at 26 °C.

On the other hand, given that thermal comfort is affected by demographic, individual, and environmental factors in addition to meteorological parameters, it is possible to note that indoor T_a and RH are not the only factors affecting thermal load on the human body and, subsequently, sleep quality. Within this scope, exploring the thermal load on the human body can help understand the overall thermal comfort of humans and its effects on sleep quality. The thermal load and heat balance of the human body and their relation to sleep quality can be measured through the utilization of thermal indices [20–22]. Several studies have been carried out to comprehend the relationship between overall thermal comfort and sleep quality using thermal indices [23–27]. Nonetheless, these studies focused on the predicted mean vote, predicted percentage of dissatisfied, and standard effective temperature, which are thermal indices only suitable for indoor measurements [28]. On the other hand, the physiologically equivalent temperature (PET) index is suitable for both indoor and outdoor assessments of physiological thermal comfort [29,30]. The PET index is an energy balance model (EBM) index that can be calculated by using T_a in relation to the energy balance of the human body regulated by T_{cr}, T_{sk}, and sweating rate [21,30]. Moreover, the PET index is one of the most sensitive EBM thermal indices to the change of T_a [22,31,32]. However, there are a limited number of studies that use the PET [30,33,34] index to understand the thermal load on the human body and its relationship with sleep quality [35,36].

To understand the whole thermal load on the human body, outdoor heat stress must be taken into account in addition to indoor thermal conditions, since urban energy balance is constituted by both anthropogenic and climatic heat fluxes [37]. Outdoor heat stress mainly occurs when the human body's capacity to regulate its temperature begins to diminish due to physiological, meteorological, and environmental factors [38]. Furthermore, considering that the outdoor climatic conditions encircle and influence the indoor thermal environment, exploring the interrelationship between outdoor and indoor conditions is necessary. The impact of climatic conditions on the indoor thermal environment subsequently also influences the sleep quality of occupants, who spend 90% of their life indoors [39]. More specifically, the urban heat island effect and the increasing frequency of heat waves due to climate change results in higher energy consumption for cooling in summer, thermal discomfort, and health problems [40–42]. Additionally, higher nocturnal air temperatures from urban heat islands [38,43] can disturb the sleep quality of occupants.

These adverse effects of outdoor heat stress can entail more risk in vulnerable indoor environments, particularly in uninsulated residential settings in Ankara [44]. Considering how thermal insulation was not obligatory until 2000 in Turkey [45], and the number of buildings constructed before 2000 was 384,489 in Ankara [46], it is possible to reckon that uninsulated vulnerable buildings are still widely used in Ankara. Within the easier transition of heat stress from outdoors to indoors in these uninsulated buildings, the sleep quality of a high number of occupants is at risk.

The present study is the initial study investigating sleep quality in uninsulated vulnerable indoor environments depending on local outdoor heat stress events, which are detected using newly defined local thresholds in Ankara [44]. Based on climate change detection indices (CCDI), three outdoor heat stress events were used in this study: the typical summer day (TSD_{25}), the very hot day (VHD_{33}), and the heat wave event (HWE_{31}). Furthermore, the assessment of physiological and psychological thermal comfort and the effect of this two-tiered approach on evaluations of sleep quality elaborated the unique nature of this research. In this regard, the multi-scaled and two-sided outputs of this study can contribute to the interdisciplinary approach to designing healthy living environments, which concerns interior architects, architects, urban planners, meteorologists, and decision makers.

2. Materials and Methods

2.1. Study Area

This study was conducted during the summer of 2021, between the months of June and September, in Bilkent University's Main Campus, more specifically within the housing (Lojman) area of the campus (Figure 1).

Figure 1. Study area map revealing the location of two residential construction typologies: uninsulated and insulated.

Ankara is located at a latitude of 39°55′31″ N and a longitude of 32°51′58″ E. The local climate of Ankara is Continental-Mediterranean, which means dry and hot summers [47]. Also, within Köppen–Geiger (KG) classification, the climate of the Ankara region was defined as '*Dsb*', which indicates a cold climate and dry-warm summers, as demonstrated in Table 1 [48]. However, further research revealed that the actual KG class of Ankara is '*Dsa*', which also states a cold climate but dry and hot summers [21]. In addition, the '*BSk*' and '*Csa*' classes, which show a cold-semi-arid climate and dry-hot summers, respectively, were detected for the contiguous regions of Ankara.

Table 1. Description of KG classes within Ankara [21,48].

KG Class	Description of KG Class	Specific Environmental Thresholds				
		General Classification Descriptors	Precipitation Descriptors		Temperature Descriptors	
			General Description	Climate Specification	General Description	Climate Specification
'Dsb'	Snow/cold climate and 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 $T_{mon}10 \geq 4$
'Dsa'	Snow/cold climate and 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 and 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

MAT, mean annual temperature; T_{hot}, the temperature of the hottest month; T_{cold}, the temperature of the coldest month; T_{mon10}, of months where the temperature is above 10; MAP, mean annual precipitation; P_{sdry}, precipitation of the driest month in summer; P_{wwet}, precipitation of the wettest month in winter; $P_{threshold}$, 2 number × MAT [21,48].

Measurements and questionnaires were performed in two kinds of residential settings with different construction types, which are pre-2000 and post-2000 buildings. Pre-2000 buildings were constructed in the 1980s with a traditional reinforced concrete system without thermal insulation [45]. The external wall system was comprised of only internal and external cement plasters and gas concrete briquette [49]. On the other hand, post-2000 buildings were constructed after 2000 with thermal insulation, in line with "Thermal Insulation in Buildings" (TS-825) standard. In contrast to the pre-2000 buildings, the external wall of post-2000 buildings includes 20 cm stone wool heat insulation, waterproof membrane, and travertine facade cladding [50].

2.2. Study Procedure

This research was operated with a pioneering two-tiered approach encompassing both physiological and psychological analysis under local extreme heat thresholds to understand the interrelationship between outdoor and indoor assessments of heat stress and urban conditions using PET (Figure 2). This innovative approach not only bridges the gap between different spatial scales but also illuminates the merging of physiological and psychological factors in comprehending urban thermal comfort and its effects on sleep quality.

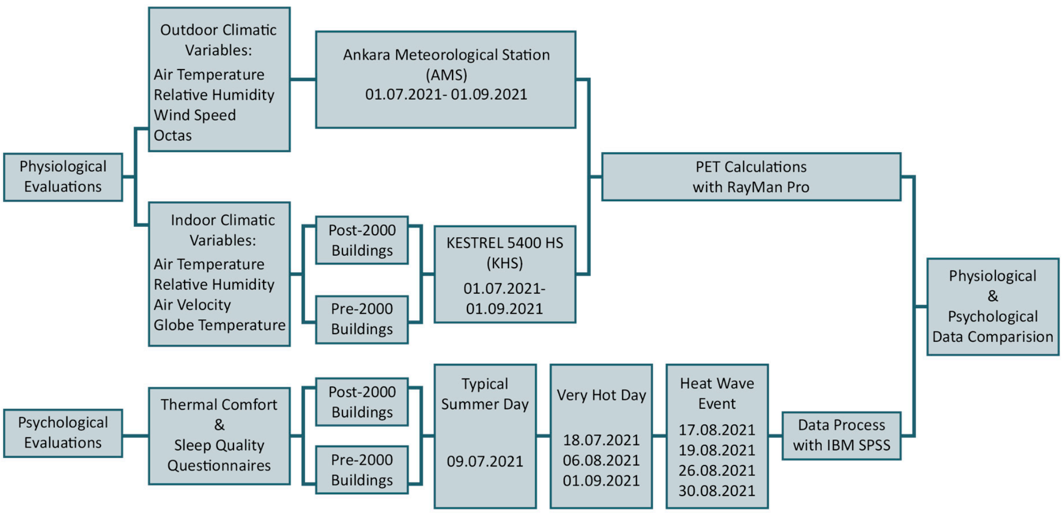

Figure 2. Research framework diagram demonstrating the two–tiered methodological approach of the study.

Within the physiological evaluations, outdoor and indoor climatic variables were collected to understand the physiological thermal comfort of dwellers from both urban and interior scales. Additionally, the outdoor climatic variables were utilized to verify the occurrence of local extreme heat thresholds; TSD_{25}, $VHD_{33,}$ and HWE_{31}. On the psychological side, thermal comfort and sleep quality questionnaires were conducted during the given local extreme heat events in each residential setting.

2.2.1. Application of Local Extreme Heat Thresholds

Within this study, different types of heat events were evaluated to consider the implication of outdoor heat events upon investigated sleep quality patterns. Such an approach interlaces with the growing need to consider outdoor conditions over indoor conditions, as suggested by several studies [38,39,51–55]. Limited work has been undertaken that could otherwise inform interdisciplinary approaches towards human health with regard to heat risk management in Ankara [21,40,44,56–59]

The application of extreme heat events was decided according to the percentile-based descriptions of locally adapted CCDIs, i.e., cool days, cool nights, warm days, and warm nights [44]. The adaptation of CCDIs for Ankara was operated regarding yearly T_a data of Ankara between 2008 and 2020 through the R-based script RClimDex. Accordingly, three extreme heat thresholds utilized in this research are TSD_{25}, VHD_{33}, and HWE_{31}, which indicate the risks of local heat stress on occupants of Ankara. TSD_{25} is the day when the maximum daily T_a exceeds 25 °C. VHD_{33} signifies the days when the maximum daily T_a is more than 33 °C (95th percentile), and HWE_{31} occurs when the daily T_a is higher than 31 °C (90th percentile) for six successive days [60–63].

2.2.2. Physiological Approach

Within this study, three local meteorological stations were used to collect outdoor and indoor climatic variables at various resolutions, including T_a and RH, which are known as the most important climatic factors affecting sleep quality according to existing studies [17,64–68]. In addition to these variables, the EMB index was applied to determine further impacts on the human biometeorological system [44,51].

In this study, outdoor and indoor meteorological parameter data were collected from 1 July to 1 September 2021. As outdoor meteorological parameters, hourly data of outdoor air temperature (T_{aOut}), outdoor relative humidity (RH_{Out}), outdoor wind speed (V_{Out}), and cloud cover (Oct) were provided by Ankara Meteorological Station (AMS) (MS#17130). As indoor meteorological parameters, indoor air temperature (Ta_{InPRE} and Ta_{InPOST}), indoor relative humidity (RH_{InPRE} and RH_{InPOST}), indoor air velocity (V_{In}), and indoor globe temperature (T_{gIn}) were collected in 10 min resolution at 1.1 m above the ground through two Kestrel Heat Stress stations (KHS) that were installed in two different residential settings (i.e., pre-2000 and post-2000 buildings) (Table 2) [51,69–74]. The subscripts of PRE and POST demonstrate the indoor meteorological parameters in pre-2000 and post-2000 building structures, respectively. Additionally, the mean radiant temperature (MRT) was calculated by Octas (Oct) for outdoor and T_{gIn} for indoor environments. The indoor mean radiant temperature (MRT_{In}) was calculated using the following equation, as identified in ISO-7726-1998 [51].

$$MRT_{In} = \left[\left(T_{gIn} + 273\right)^4 + \frac{0.25 \times 10^8}{\varepsilon} \left(\frac{\left|T_{gIn} - T_{aIn}\right|}{D} \right)^{1/4} \times \left(T_{gIn} - T_{aIn}\right) \right]^{1/4} - 273 \quad (1)$$

where: T_{gIn} is indoor globe temperature, Ta_{In} is indoor air temperature, D = 0.025 m, and ε = 0.95 (i.e., matt black).

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

Climatic Variable	Accuracy	Resolution	Specification Range
Air Temperature (T_{aIn})	0.5 °C	0.1 °C	−29.0 to 70.0 °C
Wind/Air Velocity (V_{In})	> of 3% of reading	0.1 m/s	0.6 to 40.0 m/s
Relative Humidity (RH_{In})	2%	0.1%	10 to 90% (25 °C noncondensing)
Globe Temperature (T_{gIn})	1.4 °C	0.1 °C	−29.0 to 60.0 °C

To scrutinize the physiological stress (PS) level of the human body, the PET index was calculated through outdoor and indoor climatic variables. The PET is an EBM thermal index based on the Munich Energy-Balance Model for Individuals (MEMI) [75,76], and is used to determine the impact of the thermal environment on the human body by using heat balance between them. PET is appropriate for this study because of its extensive usage in the field [32,77], suitability for both indoor and outdoor calculations [29,30], and utilization of °C as a unit of measurement [77]. Also, PET can be calculated with easily obtainable data, which are air temperature, air velocity, air humidity, and radiation [30,78,79].

Outdoor and indoor PET values (PET_{Out}, PET_{InPRE} for pre-2000 buildings, and PET_{InPOST} for post-2000 buildings) were calculated through the use of the biometeorological model RayMan Pro [29,80,81] software, which can compute the short and longwave radiation of human heat balance for local thermal environments. Outdoor and indoor meteorological parameters were imported to RayMan Pro to examine the PS grades (Table 3) on occupants of Ankara.

Table 3. Ranges of the thermal index physiologically equivalent temperature (PET) for different grades of thermal perception and physiological stress on human beings; internal heat production: 80 W, heat transfer resistance of the clothing: 0.9 clo [34]. Source: [78].

PET	Thermal Perception	Physiological Stress
	Very Cold	Extreme Cold Stress
<4 °C		
	Cold	Strong Cold Stress
8 °C		
	Cool	Moderate Cold Stress
13 °C		
	Slightly Cool	Slight Cold Stress
18 °C		
	Comfortable	No Thermal Stress
23 °C		
	Slightly Warm	Slight Heat Stress
29 °C		
	Warm	Moderate Heat Stress
35 °C		
	Hot	Strong Heat Stress
>41 °C		
	Very Hot	Extreme Heat Stress

2.2.3. Psychological Approach

Psychological thermal comfort and sleep quality of occupants were evaluated through questionnaires during each heat stress event, as displayed in Figure 2. In total, ninety-nine questionnaires were conducted with the voluntary dwellers of pre-2000 and post-2000 buildings. Each survey/heat event day was chosen according to the weekly weather predictions of AMS ($MS_{\#17130}$), and subjects were briefed one week before each survey day through an email. The participants were asked to fill out the questionnaire on the morning of the day after the heat events by considering their previous night's thermal conditions and sleep quality. Also, the subjects were informed about the process through the validated consent form by the Bilkent University Ethics Committee.

Psychological assessment of thermal load on the human body and sleep quality requires a comprehensive approach, including several factors such as demographic conditions, bed insulation, ventilation, thermal sensation, thermal comfort, thermal expectation, and thermal adaptation [82–87]. Therefore, the Questionnaire Sheet S1 is structured around four main parts: (1) general participant information, (2) sleeping conditions and behaviours, (3) climatic perception, and lastly, (4) sleep quality (Figure 3). In the first part, the subjects were asked for individual information such as age, gender, having a sleep disorder, and being outdoors during the last 24 h. The following part includes questions about sleeping conditions, i.e., sleepwear level, bed covering level, mechanical ventilation usage (with air conditioning or other devices), and window opening behaviour of the participants. In the third part, subjects were requested to self-evaluate their thermal comfort and thermal sensations in terms of overall comfort, air temperature sensation, humidity sensation, and air velocity sensation, with a 7-point scale assessment in accordance with ASHRAE Standard [88]. Within the last part, participants' sleep quality was measured through a 5-point scale of sleep quality questions consisting of sleep calmness, ease of falling asleep, ease of awakening, freshness after awakening, sleep satisfaction questions, and adapted sleep sufficiency and frequency of awakening questions.

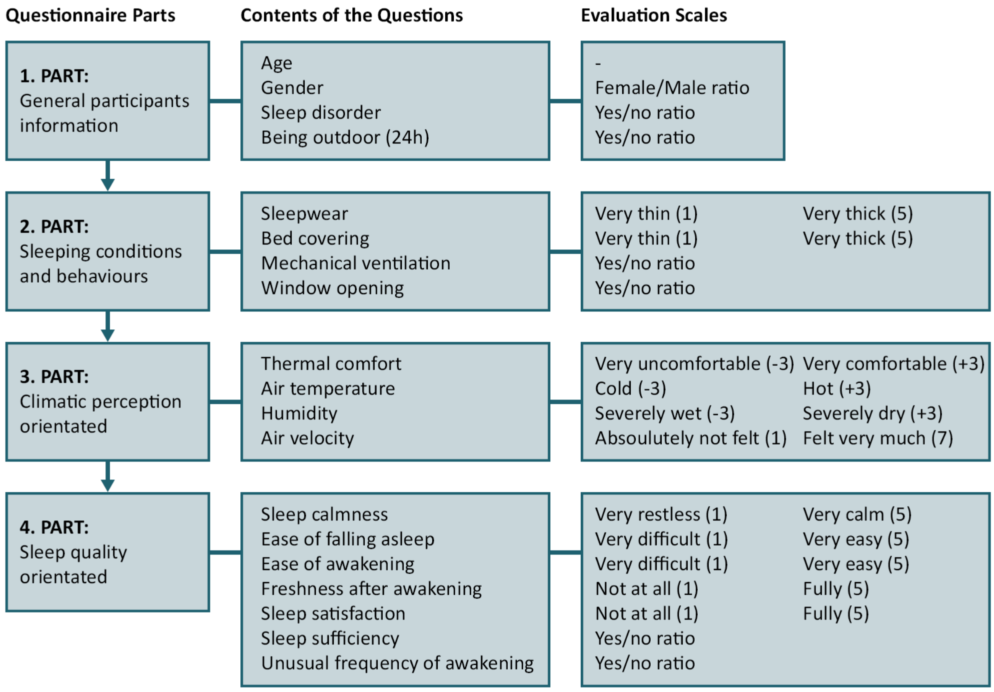

Figure 3. Psychological approach flow diagram explaining the division of questionnaire parts that are cross–examined against question contents and evaluation scales.

In the third part of the questionnaire, participants were asked to assess their psychological thermal sensations and comfort to compare with the physiological thermal comfort of occupants, as shown in Figure 3. Participants evaluated their thermal comfort using a 7-point scale of psychological thermal comfort votes (TCV) before going to sleep during the night-time of extreme heat event days [1,89]. Also, corresponding to T_{aIn} of the physiological side, air temperature sensation was evaluated through the ASHRAE 7-point scale [88] standard [6,18,19,24,83,86,90–92]. Similarly, humidity sensations were assessed to compare with the physiological RH measurements. Moreover, air velocity sensations were voted to investigate the effect of ventilation on thermal sensations. Both humidity and air velocity sensation questions and their 7-point scale evaluation types were adapted from several studies [82,84,93,94].

Within the last part of the questionnaire (Figure 3), participants were requested to evaluate their sleep quality to explore the alterations in the indoor sleep quality of occupants by using the PET index in relation to outdoor heat stress events. As the most used sleep quality determinants, sleep calmness, ease of falling asleep, ease of awakening, feeling refreshed after awakening, and sleep satisfaction were evaluated by a 5-point scale [1,6,18,84,91]. In addition, to learn the subjects' overall sleep evaluation and its relationship with specific heat events, sleep sufficiency, and unusual frequency of awakening, questions were adapted [5,19,24,83,86,90,94–96].

2.3. Data Processing

The physiological evaluations of Ta, RH, and PET values for particular heat events and identification of local heat thresholds through daily Ta_{Out} were represented through Climate-Tourism/Transfer-Information-Scheme (CTIS) [97–99] heatmaps. For an illustration of daily T_a and PET datasets, PS grades were used for comparison purposes. In addition, for benchmarking indoor thermal conditions in pre-2000 and post-2000 buildings upon outdoor heat stress during pre-sleep and sleep periods, tables were utilized that demonstrate the average, maximum, and minimum values of Ta, RH, and PET between the hours of 18:00 and 05:00. Within the psychological assessments, the mean values [86,92] and the ratio of answers were processed through frequency tables under the descriptive statistics in IBM SPSS version 26.

3. Results

3.1. Identification of Local Heat Thresholds

To validate the physiological heat stress risks of outdoor heat events on indoor thermal comfort and sleep quality, the local heat stress thresholds were identified using daily T_a values of Ankara at a 1 h resolution for 1 July 2021–2 September 2021. Based on CCDIs, TSD_{25}, VHD_{33}, and HWE_{31} events were detected as the local extreme heat events of Ankara, as illustrated in Figure 4. Additionally, monthly tropical nights (MTR_{20}) were also elicited to emphasize the high night-time outdoor heat stress risk during July and August.

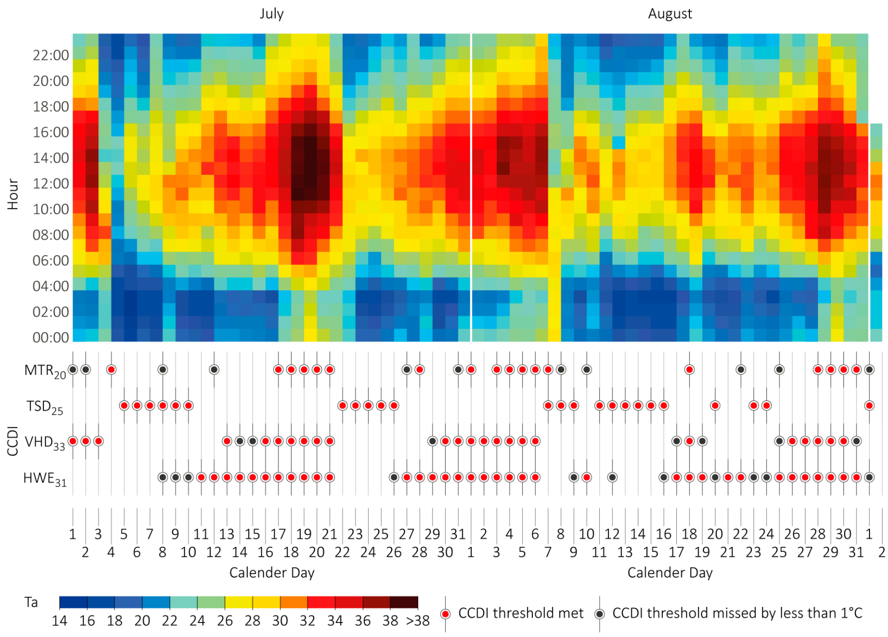

Figure 4. CTIS heatmap for identification of extreme heat events in Ankara urban centre using daily T_a data with 1 h resolution, between 1 July 2021 and 2 September 2021.

The first and foremost result obtained by the CTIS heatmap revealed that at least one extreme heat event occurred on each day during July and August without exception. Furthermore, the concurrent occurrence of extreme heat events provided comprehension of the amplified vulnerability of indoors to outdoor heat stress. For example, when considering 10 of 24 TSD_{25} events overlapped with the days missed meeting the HWE_{31} threshold by less than 1 °C, it was possible to verify that almost half of the TSD_{25}s had the potential to be a part of heat waves. More critically, it was noted that except for the first three days of July, all VHD_{33}s, including 21 VHD_{33}s and 7 potential VHD_{33}s, were also part of HWE_{31}s. It was also found that 60% of these days that witnessed both VHD_{33} and HWE_{31} events also included MTR_{20}. In other words, the identification of local heat thresholds of Ankara for July and August confirmed the extreme outdoor heat stress risks on vulnerable indoor environments during particular heat event survey dates, which are designated in Figure 2.

3.2. Evaluation of Meteorological Factors Affecting Physiological Thermal Comfort

The undertaken analysis was conducted to understand the relationship between outdoor and indoor T_a, RH, and PET, using hourly and average meteorological datasets for TSD_{25}, VHD_{33}, and HWE_{31} events. The TSD_{25} surveys were completed in one day. However, the VHD_{33} and HWE_{31} surveys were filled during different heat event days, given the decreased frequency of these heat events in comparison to typical summer conditions. Thus, VHD_{33} and HWE_{31} results were obtained using average hourly PET, T_a, and RH values. These hourly data of T_a, RH, and PET were represented through CTIS heatmaps to show the hourly course of given data. The T_a and PET heatmap keys were determined according to the PS grades to be able to compare the heat load data with heat stress grades.

3.2.1. Air Temperature

When considering measured T_a values, it was possible to identify that they were always higher in the pre-2000 buildings than those from post-2000, as presented in Figure 5. This difference became more dramatic during the pre-sleep and during sleep periods, as displayed in Table 4. With regards to the TSD_{25}, at 00:00, Ta_{Out} was lower than T_{aIn} values at 21.6 °C, while T_{aInPRE} was 26.5 °C and Ta_{InPOST} was 26.7 °C (Figure 5). Then between the hours of 00:00 and 12:00, T_{aOut}, T_{aInPRE}, and $T_{aInPOST}$ presented a variation of +8.4 K, +1.3 K, and +0.4 K, respectively. From 12:00 to 18:00, T_{aOut} decreased by −6.6 K, while T_{aInPRE} increased by +0.9 K, and $T_{aInPOST}$ slightly decreased by −0.1 K. The drop in average T_{aOut} and $T_{aInPOST}$ continued by −2.3 K and −0.2 K, respectively, during the nocturnal period, i.e., between 18:00 and 05:00. In contrast, T_{aInPRE} kept rising by +1.0 K (Table 4).

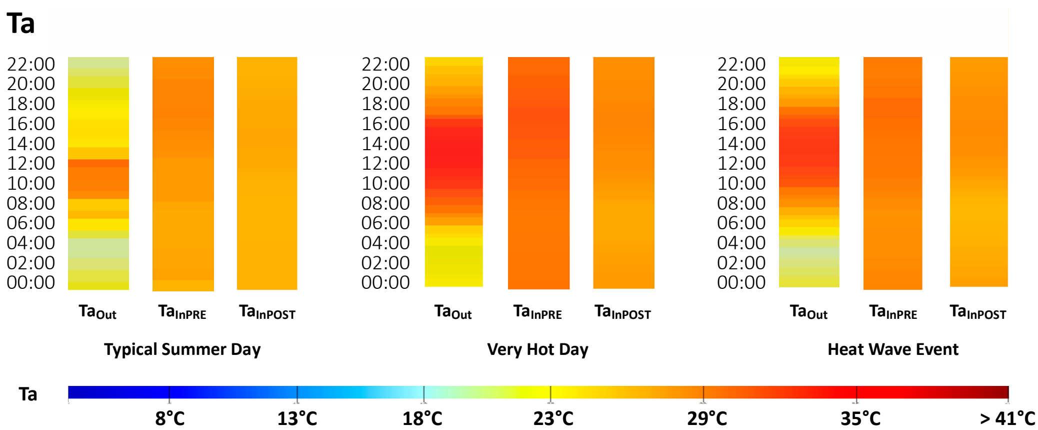

Figure 5. CTIS heatmaps for T_a values of pre-2000 and post-2000 buildings during the TSD_{25}, VHD_{33}, and HWE_{31} events.

Table 4. Average, maximum, and minimum values of T_{aOut}, T_{aInPRE}, and $T_{aInPOST}$ for before sleep and sleep hours during TSD_{25}, VHD_{33}, and HWE_{31} events.

T_a (°C) (Average)		T_{aOut}				T_{aInPRE}				$T_{aInPOST}$			
Time Intervals		**18:00–20:00**	**21:00–23:00**	**00:00–02:00**	**03:00–05:00**	**18:00–20:00**	**21:00–23:00**	**00:00–02:00**	**03:00–05:00**	**18:00–20:00**	**21:00–23:00**	**00:00–02:00**	**03:00–05:00**
TSD_{25}	Average	22.3	20.0	17.7	20.0	28.7	28.3	29.6	29.7	26.9	26.6	26.7	26.7
	Max	23.4	20.7	18.3	22.5	28.8	28.4	30.0	29.8	27.0	26.7	26.8	26.8
	Min	24.1	21.3	17.2	17.3	28.7	28.2	29.0	29.7	26.8	26.6	26.7	26.7
VHD_{33}	Average	27.5	25.0	22.9	23.2	30.7	30.0	29.9	29.7	28.4	28.2	27.7	27.4
	Max	28.7	25.9	23.6	23.2	30.9	30.1	30.0	29.8	28.5	28.3	27.9	27.5
	Min	26.7	24.1	22.4	21.9	30.5	30.0	29.8	29.7	28.3	28.1	27.6	27.2
HWE_{31}	Average	26.5	22.9	20.3	20.3	29.5	29.1	28.9	28.7	28.0	27.6	27.2	26.8
	Max	27.7	24.0	21.1	22.3	29.9	29.1	29.0	28.8	28.2	27.8	27.5	26.9
	Min	25.4	21.9	19.6	18.8	29.2	29.1	28.8	28.6	27.9	27.5	27.0	26.7

TSD_{25}, typical summer day when the maximum daily T_a exceeds 25 °C; VHD_{33}, very hot day when the maximum daily T_a exceeds 33 °C; HWE_{31} heat wave event when the daily T_a exceeds 31 °C for six successive days; T_{aOut}, outdoor air temperature; T_{aInPRE}, air temperature in pre-2000 buildings; $T_{aInPOST}$, air temperature in post-2000 buildings.

As delineated in Figure 5, T_{aOut}, T_{aInPRE}, and $T_{aInPOST}$ values were highest during the VHD_{33}s compared with TSD_{25} and HWE_{31}s. Within the VHD_{33}s, at 00:00, T_{aOut}, T_{aInPRE}, and $T_{aInPOST}$ values were 23.2 °C, 29.7 °C, and 27.8 °C respectively. At 12:00, T_a values surpassed those of the morning hours by up to +10.7 K, +0.6 K, and +0.4 K. Until 18:00, T_{aOut} showed a significant drop of −5.2 K, while on the contrary, T_{aInPRE} and $T_{aInPOST}$ presented a slight increase of +0.7 K and +0.4 K, respectively. Between the hours of 18:00 and 05:00, the average T_{aOut} values indicated higher variation than T_{aInPRE} and $T_{aInPOST}$ values by −4.3 K, −1.0 K, and −1.0 K, as depicted in Table 4. It was also notable to state that the difference between average T_{aInPRE} and $T_{aInPOST}$ increased by +0.5 K between 21:00 and 05:00.

In the case of HWE_{31}s, T_a values were lower than VHD_{33}s but higher than TSD_{25}. Figure 5 demonstrates that at 00:00, T_{aOut} was 21.4 °C, T_{aInPRE} was 28.7 °C, and $T_{aInPOST}$ was 27.4 °C. Around 12:00, T_{aOut} designated a considerable rise of +11.1 K, while T_{aInPRE} and $T_{aInPOST}$ values showed a small increase of +0.6 K and +0.5 K. Until 18:00, even though the T_{aOut} decreased by −4.7 K, T_{aInPRE} and $T_{aInPOST}$ values kept rising to +0.7 K and +0.3 K, respectively. As presented in Table 4, all average T_a values reached lower values throughout the nocturnal period. Notably, during the hours between 21:00 and 23:00, the difference between average T_{aInPRE} and $T_{aInPOST}$ was 1.5 °C, and this difference rose by +0.4 K during the sleep period until 05:00.

To sum up, the relationship between the hourly course of T_{aOut}, T_{aInPRE}, and $T_{aInPOST}$ was similar during all three heat events. Ta_{Out} always had lower values than $Ta_{In}PRE$ and $T_{aInPOST}$ in the mornings. Then, all T_a values increased during the afternoon, and T_{aOut} values became considerably higher than the T_{aInPRE} and $T_{aInPOST}$ values until 18:00. However, after 18:00, all T_a values began to decrease, but the amount of decrease was consistently higher for T_{aOut}, while almost always, T_{aInPRE} and $T_{aInPOST}$ values declined only slightly. Exceptionally, the T_{aInPRE} values slightly increased during the TSD_{25} night. Also, when the T_{aInPRE} and $T_{aInPOST}$ were compared, it was revealed that the difference between them kept rising during the pre-sleep and sleep periods.

3.2.2. Relative Humidity

This study measured outdoor and indoor humidity as one of the most investigated meteorological factors influencing thermal comfort and sleep quality. Humidity can be identified through several parameters, including relative humidity, vapor pressure, dew point temperature, and humidity rate [100]. Particularly, RH was examined in this study as a representative of the partial vapor pressure of the environment [88] through the CTIS heatmap (Figure 6) and the average nocturnal period values table (Table 5).

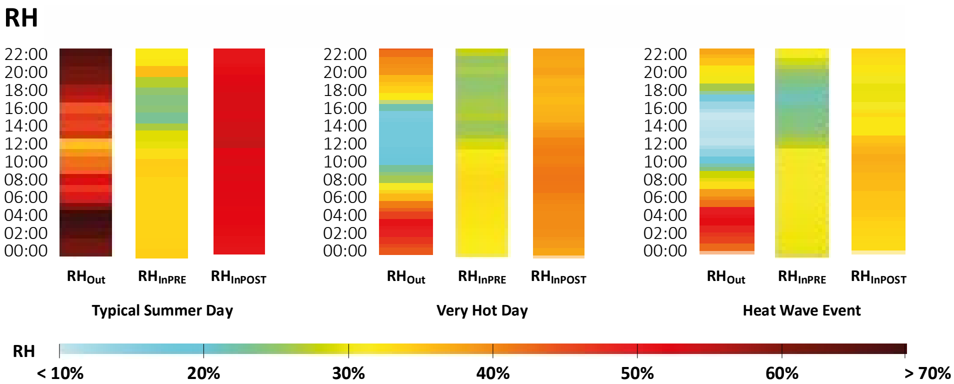

Figure 6. CTIS heatmaps for RH values of pre-2000 and post-2000 buildings during the TSD_{25}, VHD_{33}, and HWE_{31} events.

Table 5. Average, maximum, and minimum values of RH_{Out}, RH_{InPRE}, and RH_{InPOST} for before-sleep and sleep hours during TSD_{25}, VHD_{33}, and HWE_{31} events.

RH (%) (Average)		RH_{Out}				RH_{InPRE}				RH_{InPOST}			
Time Intervals		**18:00–20:00**	**21:00–23:00**	**00:00–02:00**	**03:00–05:00**	**18:00–20:00**	**21:00–23:00**	**00:00–02:00**	**03:00–05:00**	**18:00–20:00**	**21:00–23:00**	**00:00–02:00**	**03:00–05:00**
TSD_{25}	Average	60.0	67.0	75.0	63.0	29.1	31.9	29.2	30.0	52.2	51.8	54.9	55.5
	Max	62.0	69.0	77.0	76.0	35.5	32.1	29.6	31.0	52.8	53.9	55.1	55.8
	Min	57.0	65.0	73.0	49.0	24.9	31.7	28.9	29.2	51.6	50.8	54.8	55.4
VHD_{33}	Average	36.0	42.4	49.2	49.3	25.5	27.1	30.4	31.2	37.0	37.9	38.0	39.0
	Max	39.0	45.0	50.0	51.0	27.0	28.8	30.8	31.5	38.0	38.5	38.3	38.9
	Min	34.0	40.0	48.0	48.0	24.8	24.8	29.8	31.0	36.3	37.3	37.6	38.5
HWE_{31}	Average	29.5	37.9	45.3	47.0	23.9	30.4	31.6	31.2	30.8	33.5	34.8	35.3
	Max	32.2	41.2	47.5	49.7	25.2	31.7	31.7	31.4	32.2	34.3	35.3	35.5
	Min	26.2	35.0	43.0	43.5	22.4	28.7	31.6	31.2	29.7	32.7	34.2	35.2

TSD_{25}, typical summer day when the maximum daily T_a exceeds 25 °C; VHD_{33}, very hot day when the maximum daily T_a exceeds 33 °C; HWE_{31} heat wave event when the daily T_a exceeds 31 °C for six successive days; RH_{Out}, outdoor relative humidity; RH_{InPRE}, relative humidity in pre-2000 buildings; RH_{InPOST}, relative humidity in post-2000 buildings.

The results indicated that both RH_{Out} and RH_{In} values were highest during the TSD_{25} compared with the VHD_{33}s and HWE_{31}s, as shown in Figure 6. Within the case of TSD_{25}, at 00:00, the RH_{Out} was 61.0% and had higher values than RH_{InPRE} and RH_{InPOST}, which were 34.1% and 50.8%, respectively. Until 12:00, RH_{In}POST kept slightly increasing by +3.8 K, while on the contrary, RH_{Out} and RH_{InPRE} showed a drop of −26.0% and −4.5%. At 18:00, despite a significant increase in RH_{Out} of up to +22.0 K, RH_{InPRE} and RH_{InPOST} values did not increase and presented a reverse variation of −4.7 K and −1.8 K, respectively. As demonstrated in Table 5, between 18:00 and 05:00, all average RH values showed a slight increase of +3.0 K, +0.9 K, and +3.3 K.

During the VHD_{33}s, at 00:00, RH_{Out} was 44.3%, RH_{InPRE} was 31.5%, and RH_{InPOST} was 37.6%, which were considerably lower than those of TSD_{25}. At 12:00, RH_{Out} marked a considerable decrease of −27.0 K, while RH_{InPRE} and RH_{InPOST} indicated a slight variation of −2.6 K and +2.8 K, respectively. During 18:00, RH_{Out} reaches higher values of up to +16.3 K. On the contrary, RH_{InPRE} and RH_{InPOST} presented a small drop of −4.0 K and −3.7 K. Nevertheless, the average RH_{Out}, RH_{InPRE}, and RH_{InPOST} values for the nocturnal period (Table 5) revealed that all RH values rose by +13.3 K, +5.7 K, and +2.0 K between 18:00 and 05:00.

Similar to the TSD_{25} and VHD_{33s}, within the HWE_{31}s, the RH_{Out} had a higher value of 42.5% than RH_{InPRE} (29.6%) and RH_{InPOST} (33.1%) at 00:00 too. However, at 12:00, RH_{Out} presented a significant decrease of −32.0 K, while RH_{InPRE} and RH_{InPOST} slightly varied by −2.0 K and +1.9 K. Around 18:00, it was witnessed that RH_{Out} rose by +15.8 K. In comparison, RH_{InPRE} and RH_{InPOST} varied only by −5.2 K and −5.3 K. For the pre-sleep and sleep periods, the vulnerability of the indoors became more dramatic during the nocturnal period, as manifested through the increase in $RH_{Out,}$ RH_{InPRE}, and RH_{InPOST} by +17.5 K, +7.3 K, and +4.5 K (Table 5) between 18:00 and 05:00.

3.2.3. Thermal Index Outputs

In addition to the investigated T_a and RH, this study used the PET thermal index to understand the physiological thermal load on the human body and its relationship with sleep quality. Figure 7 displays the hourly change in $PET_{Out,}$ PET_{InPRE}, and PET_{InPOST} during local extreme heat events. In TSD_{25}, at 00:00, with 17.3 °C, PET_{Out} was lower than PET_{In} values, while both PET_{InPRE} and PET_{InPOST} were 27.5 °C. Nonetheless, until 12:00, PET_{Out} surpassed PET_{In} values by +16.3 K, and PET_{InPRE} and PET_{InPOST} values presented a slight variation by +0.7 K and +0.4 K. Until 18:00, PET_{InPRE} increased by +0.8 K, while PET_{Out} and PET_{InPOST} decreased by −14.0 K, −0.1 K, respectively. For the nocturnal period, Table 6 revealed that between 18:00 and 05:00, the variation in average PET_{Out} was higher by −2.7 K than that in PET_{InPRE} and PET_{InPOST}, which varied by +0.9 K and −1.0 K, respectively.

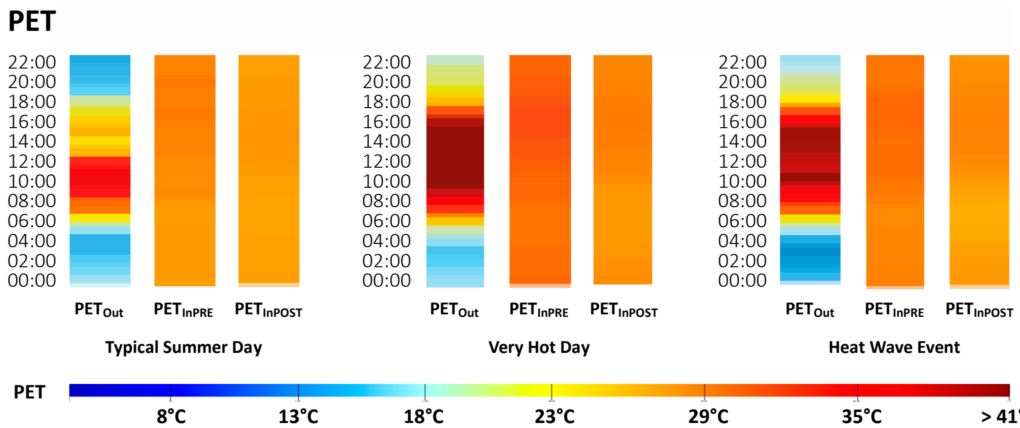

Figure 7. CTIS heatmaps for PET values of pre-2000 and post-2000 buildings during the TSD_{25}, VHD_{33}, and HWE_{31} events.

Therefore, the average PET_{InPRE} and PET_{InPOST} remained higher than PET_{Out} between 18:00 and 05:00. Moreover, when the PET_{InPRE} and PET_{InPOST} were compared, it was seen that the difference between them increased by +1.1 K between 21:00 and 05:00.

In the case of VHD_{33}, PET_{Out}, PET_{InPRE}, and PET_{InPOST} values were consistently higher than the ones in TSD_{25} and HWE_{31}. At 00:00, PET_{Out} was 17.2 °C, PET_{InPRE} was 30.1 °C, and PET_{InPOST} was 28.3 °C (Figure 7). Until 12:00, PET_{Out} reached 43.5 °C, which indicates the extreme heat stress within PS grades. Meanwhile, PET_{InPRE} and PET_{InPOST} showed notably smaller variations by +0.7 K and +0.5 K, respectively. In contrast to the afternoon, at 18:00, PET_{Out} decreased significantly by −17.3 K, while PET_{InPRE} and PET_{InPOST} began to increase by +0.4 K and +0.2 K. As shown in Table 6, all average PET values declined throughout the pre-sleep and sleep periods. It was crucial to signify that between 18:00 and 05:00, PET_{Out} varied by −4.5 K, while PET_{InPRE} and PET_{InPOST} showed slight variation by −0.9 K and −1.0 K. Thus, although the PET_{InPRE} and PET_{InPOST} values were lower than PET_{Out} during the diurnal period, they remained higher than PET_{Out} in the nocturnal period. Also, when the residential settings were compared between 21:00 and 05:00, it was found that the difference between PET_{InPRE} and PET_{InPOST} denoted an increase of +0.5 K.

Table 6. Average, maximum, and minimum values of PET_{Out}, PET_{InPRE}, and PET_{InPOST} for before-sleep and sleep hours during TSD_{25}, VHD_{33}, and HWE_{31} events.

PET (°C) (Average)		PET_{Out}				PET_{InPRE}				PET_{InPOST}			
Time Intervals		**18:00–20:00**	**21:00–23:00**	**00:00–02:00**	**03:00–05:00**	**18:00–20:00**	**21:00–23:00**	**00:00–02:00**	**03:00–05:00**	**18:00–20:00**	**21:00–23:00**	**00:00–02:00**	**03:00–05:00**
TSD_{25}	Average	16.9	14.4	12.4	14.2	29.1	28.7	30.0	30.0	27.7	27.4	27.6	27.6
	Max	19.6	15.0	12.7	16.7	29.4	28.8	30.3	30.1	27.8	27.5	27.6	27.7
	Min	15.2	13.8	12.0	11.5	29.0	28.6	29.5	30.0	27.6	27.4	27.6	27.6
VHD_{33}	Average	22.9	19.0	17.3	18.4	30.9	30.3	30.2	30.0	28.9	28.7	28.3	27.9
	Max	26.2	20.3	18.0	20.5	31.2	30.4	30.3	30.1	29.0	28.8	28.5	28.1
	Min	20.8	18.0	16.7	16.6	30.7	30.3	30.2	30.1	28.8	28.6	28.2	27.8
HWE_{31}	Average	21.5	17.2	15.1	15.1	29.8	29.5	29.4	29.1	28.4	28.0	27.7	27.3
	Max	24.1	18.1	15.9	16.7	30.2	29.6	29.5	29.2	28.6	28.2	27.9	27.4
	Min	19.7	16.4	14.4	13.6	29.5	29.5	29.3	29.0	28.3	27.9	27.5	27.1

TSD_{25}, typical summer day when the maximum daily T_a exceeds 25 °C; VHD_{33}, very hot day when the maximum daily T_a exceeds 33 °C; HWE_{31} heat wave event when the daily T_a exceeds 31 °C for six successive days; PET_{Out}, outdoor air temperature; PET_{InPRE}, air temperature in pre-2000 buildings; PET_{InPOST}, air temperature in post-2000 buildings.

Within the HWE_{31}s, at 00:00, PET_{Out} was 15.0 °C and lower than PET_{InPRE} and PET_{InPOST}, which were 29.0 °C and 27.8 °C, respectively (Figure 7). At the hour of 12:00, PET_{Out} increased to 39.4 °C, which corresponds to strong heat stress in PS grades (Table 3). In the same period, PET_{InPRE} and PET_{InPOST} were altered only by +0.7 K and +0.7 K. Between the hours of 12:00 and 18:00, PET_{Out} marked a notable drop of −15.3 K. On the contrary, PET_{InPRE} and PET_{InPOST} stayed in higher values by variations of +0.5 K and +0.1 K, respectively. As articulated in Table 6, and similar to VHD_{33}s, all PET values declined between 18:00 and 05:00 by variations of −6.4 K, −0.7 K, and −1.1 K, respectively. More critically, from 21:00 to 05:00, the difference between PET_{InPRE} and PET_{InPOST} was raised by +0.3 K.

In brief, the hourly and average PET values verified that generally, PET_{Out} values were lower than PET_{InPRE} and PET_{InPOST} values in the morning, but surpassed them and reached elevated PS grades during the afternoon. Nevertheless, when it comes to the nocturnal period, PET_{InPRE} and PET_{InPOST} became markedly higher than PET_{Out} again. Moreover, the difference between PET_{InPRE} and PET_{InPOST} increased persistently between 21:00 and 05:00 during all outdoor heat events, with higher values of PET_{InPRE}.

3.3. Psychological Evaluations

The results of psychological evaluations were derived from the four-part analysis of the qualitative attributes from the questionnaires undertaken during identified local thresholds: TSD_{25}, VHD_{33}, and HWE_{31}. Within this scope, the results of parts 1 and 2 will be summarized under individual conditions, while the results of parts 3 and 4 will be launched as a psychological evaluation of thermal conditions and evaluation of sleep quality sections.

3.3.1. Individual Conditions

As presented in Figures 8 and 9, and Table 7, it was possible to determine the individual conditions of participants from each residential setting for all heat events in Ankara. With regard to the demographic information of participants, it was revealed that the subjects' ages were consistently higher in pre-2000 buildings than in post-2000 buildings during all heat events (Figure 8). The gender ratio was always balanced between residential settings. None of the participants had sleep disorders. Moreover, as the last component of part 1, being outdoor ratios were illustrated in Figure 9, which signified that the ratio of subjects that had been outdoors during the 24 h before the survey day was continually higher in pre-2000 buildings than in post-2000 buildings.

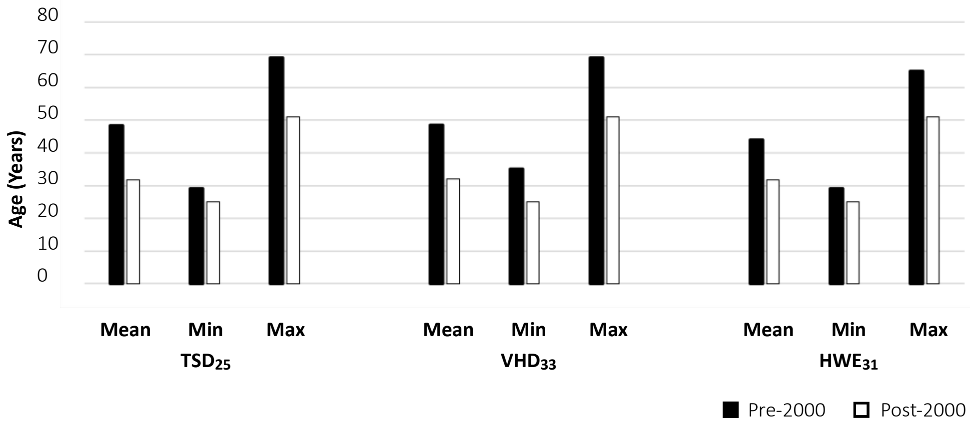

Figure 8. Mean, minima, and maxima of ages of participants from pre- and post-2000 buildings during outdoor heat events.

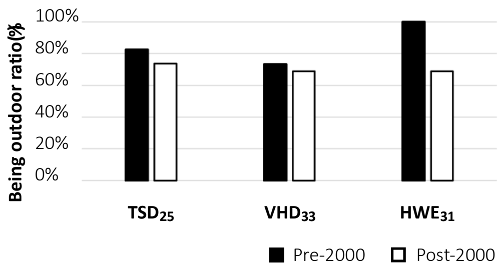

Figure 9. Being outdoor ratio of participants from pre- and post-2000 buildings during outdoor heat events.

Table 7. Mean bed insulation values and ventilation ratios for pre- and post-2000 buildings during outdoor heat events.

	TSD_{25}		VHD_{33}		HWE_{31}	
	Pre-2000	**Post-2000**	**Pre-2000**	**Post-2000**	**Pre-2000**	**Post-2000**
Mean Sleepwear Level	2.71	2.05	2.27	2.13	1.88	1.88
Mean Bed Covering Level	3.24	2.58	2.53	2.25	2.40	2.06
Window Opening Ratio (yes)	29.4%	47.4%	53.3%	75.0%	56.3%	75.0%
Mechanical Ventilation Ratio (yes)	11.8%	5.3%	6.7%	12.5%	18.8%	25.0%

Table 7 enables one to be informed about participants' sleeping conditions and behaviour during each heat event. Regarding mean votes, it is possible to verify that both sleepwear and bed covering levels were always higher in pre-2000 buildings than post-2000 buildings during all heat events (only except for similar sleepwear levels during HWE_{31}). On the contrary, the window opening ratio was always higher in the post-2000 buildings than in the pre-2000 buildings. During all heat events, some participants used mechanical ventilation, such as air conditioners. During the TSD_{25}, the ratio of participants who used mechanical ventilation before sleeping was higher in pre-2000 buildings than the post-2000 buildings, while there was a reverse situation during the VHD_{33} and HWE_{31} events.

3.3.2. Psychological Evaluation of Thermal Conditions

The results of psychological thermal comfort evaluations from questionnaires inclusive of mechanical ventilation users were indicated in Table 8. Considering mean TCV, it was possible to confirm for both residential settings that the thermal comforts of participants were highest during the TSD_{25} and lowest during the HWE_{31}s. On the other hand, the mean thermal sensation vote (TSV) was highest during the HWE_{31}s in both pre-2000 and post-2000 buildings. The mean humidity sensation vote (HSV) was highest within HWE_{31}s in pre-2000 buildings, while highest during VHD_{33}s in post-2000 buildings. The mean air velocity sensation vote (ASV) was highest during the VHD_{33}s for each residential setting.

Table 8. Psychological thermal comfort evaluation results from questionnaires inclusive of users of mechanical ventilation.

	TSD_{25}		VHD_{33}		HWE_{31}	
	Pre-2000	**Post-2000**	**Pre-2000**	**Post-2000**	**Pre-2000**	**Post-2000**
Mean TCV	1.41	1.11	0.20	0.63	−0.31	−0.69
Mean TSV	0.18	0.16	0.40	−0.12	1.06	1.56
Mean HSV	0.24	0.42	0.27	0.06	−0.06	0.25
Mean ASV	3.00	3.16	3.07	3.69	2.50	3.19

TCV, thermal comfort vote; TSV, thermal sensation vote; HSV, humidity sensation vote; ASV, air velocity sensation vote.

Comparing the TCVs of residential settings revealed that pre-2000 building participants had higher TCVs during TSD_{25} and HWE_{31}s than those of post-2000, while the reverse was the case for the VHD_{33}s. The mean TSVs were slightly higher in pre-2000 buildings during TSD_{25} and significantly higher in pre-2000 buildings during VHD_{33}s and post-2000 buildings during HWE_{31}s. The mean HSVs were higher in pre-2000 buildings during the TSD_{25} and HWE_{31}s, while higher in post-2000 buildings during the VHD_{33}s. The ASVs were consistently higher in post-2000 buildings during all heat events. It was also worth noting that the difference between residential settings in ASVs was higher during the VHD_{33}s.

The results of physiological thermal comfort evaluations from questionnaires non-inclusive of users of mechanical ventilation are displayed in Table 9. Compared to the previous results that included users of mechanical ventilation, TCVs of both residential settings increased during all heat events. Mainly, since TCVs increased more in post-2000 buildings than in pre-2000 buildings during the VHD_{33}s and HWE_{31}s, the difference between residential settings increased for VHD_{33}s and decreased during HWE_{31}s. On the other hand, the overall TSVs decreased when the users of mechanical ventilation were excluded, except the TSV of pre-2000 buildings in TSD_{25}. In particular, the difference in TSVs between residential settings showed an increase in VHD_{33}s and a drop in HWE_{31}s. When the results of the HSVs were examined, it was seen that the difference between HSVs declined in VHD_{33}s and raised in HWE_{31}s. Lastly, the difference in ASVs between pre-and post-2000 buildings steadily decreased for all heat events, most during the VHD_{33}s.

Table 9. Psychological thermal comfort evaluation results from questionnaires noninclusive of users of mechanical ventilation.

	TSD_{25}		VHD_{33}		HWE_{31}	
	Pre-2000	**Post-2000**	**Pre-2000**	**Post-2000**	**Pre-2000**	**Post-2000**
Mean TCV	1.47	1.17	0.29	0.86	−0.15	−0.33
Mean TSV	0.20	0.11	0.36	−0.29	0.92	1.25
Mean HSV	0.27	0.44	0.21	0.07	−0.08	0.42
Mean ASV	3.00	3.06	3.21	3.57	2.54	2.92

TCV, thermal comfort vote; TSV, thermal sensation vote; HSV, humidity sensation vote; ASV, air velocity sensation vote.

3.3.3. Evaluation of Sleep Quality

When considering sleep quality evaluations, as demonstrated in Figure 10, it was possible to determine the mean votes of each sleep quality parameter for the two residential settings during the different respective heat events. Within the overall inspection of sleep quality evaluations in pre-2000 buildings, it was found that sleep quality votes/ratios (SQV) were highest during TSD_{25}, except for the sleep sufficiency that was highest within VHD_{33}s. Also, the unusual frequency of awakening ratios (answer of Yes) was lowest during the TSD_{25} in pre-2000 buildings. On the other side, in post-2000 buildings, the highest votes for calmness of sleep, ease of falling asleep, and the lowest ratio of the unusual frequency of awakening were witnessed in TSD_{25}. Additionally, the sleep sufficiency ratio and mean ease of awakening, freshness after awakening, and sleep satisfaction votes were highest during VHD_{33}s in post-2000 buildings.

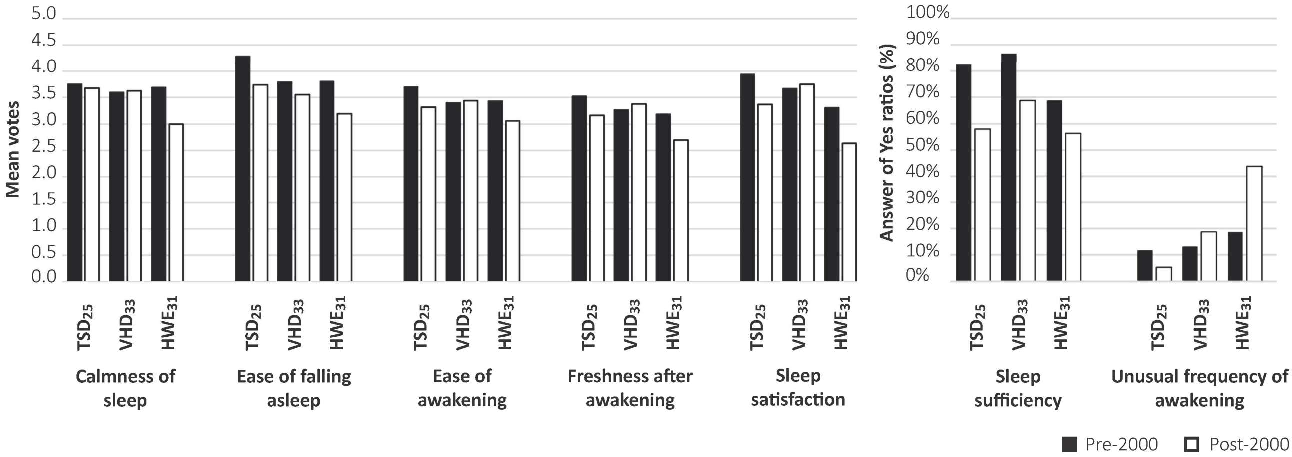

Figure 10. Sleep quality evaluation results from questionnaires inclusive of users of mechanical ventilation.

The comparison of the sleep quality evaluations between residential settings indicated that the sleep sufficiency ratio, mean calmness of sleep, and the ease of falling asleep votes were consistently higher in pre-2000 buildings during all outdoor heat events. Exceptionally, the mean calmness of sleep votes was similar between residential settings during VHD_{33}s. Moreover, the other SQVs, i.e., the mean ease of awakening, freshness after awakening, and sleep satisfaction, were higher for pre-2000 buildings during the TSD_{25} and HWE_{31}s, while they were higher in post-2000 buildings during the VHD_{33}s. As of last, the frequency of unusual awakenings votes was higher in pre-2000 buildings during TSD_{25} than in post-2000 buildings, while it was the opposite for VHD_{33}s and HWE_{31}s.

When users of mechanical ventilation were excluded (Figure 11), the mean values of sleep quality parameters improved more in favour of post-2000 buildings compared to pre-2000 ones during the TSD_{25} and VHD_{33}s, while the reverse was the case in HWE_{31}s. Within TSD_{25}, the differences in mean calmness of sleep, freshness after awakening, sleep satisfaction votes, and sleep sufficiency ratios between residential settings decreased, while the difference in unusual frequency of awakening increased. In the case of VHD_{33}s, the mean calmness of sleep and ease of falling asleep votes, as well as the sleep sufficiency ratio, declined in pre-2000 buildings and rose in post-2000 buildings. Consequently, the difference between these votes/ratios of residential settings marked an increase. Additionally, the difference in ease of awakening, freshness after awakening, and sleep satisfaction votes between the two residential settings also increased. Finally, the unusual frequency of awakening ratio increased in pre-2000 buildings and decreased in post-2000 buildings. During the HWE_{31}s, all sleep quality parameters except ease of falling asleep and ease of awakening rose in pre-2000 buildings and decreased in post-2000 buildings.

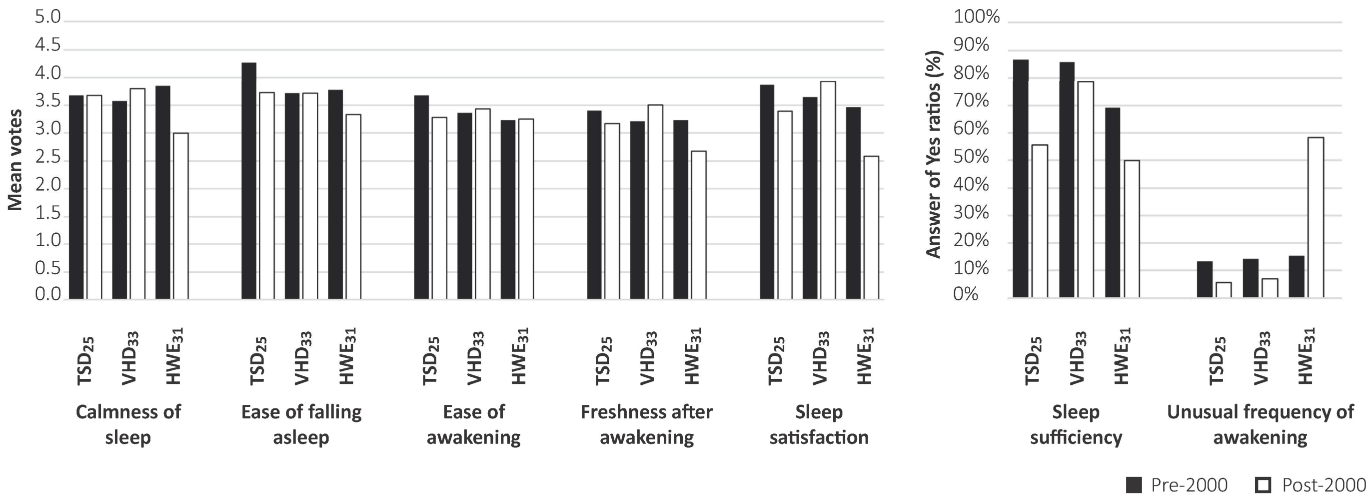

Figure 11. Sleep quality evaluation results from questionnaires noninclusive of users of mechanical ventilation.

4. Discussion

In this study, the thermal comfort and sleep quality of occupants were investigated in insulated and uninsulated buildings under local extreme heat thresholds. The results of this study pointed out that occupants' thermal comfort and sleep quality were altered during local extreme heat events. Particularly, the physiological thermal comfort of participants was highest within the TSD_{25} and lowest in VHD_{33} events, while psychological TCVs were also highest in TSD_{25} but lowest in HWE_{31}s. In the residential context, although indoor heat stress was consistently higher in uninsulated buildings than in insulated ones during all local extreme heat events, the psychological TCVs and the majority of the SQVs revealed better evaluations in insulated buildings than uninsulated ones during only the extreme conditions of VHD_{33}s.

4.1. Relationship between Physiological and Psychological Thermal Comfort

Within the disclosed findings, the highest TCVs were revealed within the TSD_{25} in both residential settings, which had different thermal conditions in the given heat threshold. Participants felt thermally comfortable when the average T_a was 28.3 °C, RH was 31.9%, and PET was 28.7 °C in pre-2000 buildings, and when the average T_a was 26.6 °C, RH was 51.8%, and PET was 27.4 °C in post-2000 buildings before sleep. The authors of [6,27] also reported that subjects felt thermally comfortable when T_a was 26 °C before sleep. On the other hand, the lowest TCVs and the highest TSVs were not expected to be during HWE_{31}s instead of VHD_{33}s, which had extreme heat stress based on PS grades. The reason for this unforeseen difference between physiological and psychological results might be that the VHD_{33}s were intertwined with HWE_{31}s during the 2021 summer in Ankara, as was also demonstrated for the 2020 summer in Ankara [44]. Also, the results confirmed a slower drop in indoor heat stress than outdoor heat stress, which can be explained by the high heat retention capacity within the mass walls of building structures [101,102].

Earlier studies identified lower psychological thermal comfort [103] and thermal performance [104–106] in uninsulated buildings. The authors of [107–109] indicated the necessity of thermal insulation to achieve thermal comfort. The findings of this study also revealed higher indoor heat stress within uninsulated buildings compared to insulated ones in all heat events. This difference in heat stress kept rising throughout the pre-sleep and sleep periods. However, the psychological thermal comfort evaluations presented opposite results, with higher TCVs in pre-2000 buildings during TSD_{25} and HWE_{31}s. Similar results were also obtained by [110], who investigated the occupants' thermal comfort in Ghademes, Libya, during summer. Their findings showed that even though the equivalent measurements indicated discomfortable conditions, participants evaluated their thermal environments as comfortable.

Considering older adults' higher thermal neutral temperatures [111,112] and bed insulation can create an isolated bed microclimate, which can result in less sensitivity to the ambient thermal conditions during sleep [86,92,113–115], it was possible to note that higher age and bed insulation levels influenced the thermal comfort evaluations of uninsulated buildings' participants. Additionally, past experiences in various environments, such as indoors and outdoors, can influence thermal sensations [116]. Particularly, thermal history can affect occupants' thermal comfort [117–119], and previous exposure to a warm environment decreases thermal sensations [120–122]. Therefore, the higher TCVs of uninsulated buildings' subjects might be associated with their short-term warmer thermal history (24 h). Contingently, long-term thermal history can provoke lower air temperature sensations [123–125]. However, given the temporal scope of this particular study to the events within the stipulated season, such associations between longer-term thermal history and thermal comfort remain an important topic for future study. Also, window opening increases the T_a and RH transmission between outdoor and indoor environments [126,127]. Hence, a higher window opening ratio in insulated buildings can affect the intriguing TCVs on TSD_{25} and HWE_{31}s. On the other hand, the generally measured RH values did not exceed 70%, whereas higher values were found to be unacceptable for thermal comfort by previous studies [100,128,129].

4.2. Relationship between Pre-Sleep Thermal Comfort and Sleep Quality

The psychological sleep quality evaluations revealed that participants of both buildings slept better in the same pre-sleep heat stress level, i.e., when the average PET_{In} was 28.7 °C, but at different heat thresholds, TSD_{25} and VHD_{33}s, respectively. These similar indoor heat stress levels indicated the integral role of insulation in reducing heat exchange between indoor and outdoor environments [130–132]. Within the same dates/times, the average Ta_{In} values were also similar, but the RH_{In} presented different values. These results verified the effectiveness of PET thermal index rather than the utilization of only T_a and RH in assessing occupants' sleep quality, in addition to the previous knowledge that PET is a convenient representative of the impacts of climatic factors on human health due to its associations with human thermoregulatory system and circadian rhythm [133].

According to the literature, exposure to heat results in poor sleep quality for older adults [68,134]. Nevertheless, previous studies showed that healthy older adults tend to evaluate their sleep quality as acceptable, although their physiological sleep measurements indicated the opposite [95,135,136]. This inconsistency was explained by older adults' lower expectations for their sleep quality. Besides that, bed insulation can improve the sleep quality of occupants [86,94] by restraining bed microclimate [92,137] and keeping skin temperature at a thermal neutral range [138]. Therefore, higher age and bed insulation levels in uninsulated buildings can explain the unexpectedly higher SQVs in uninsulated buildings compared to insulated buildings within TSD_{25} and HWE_{31}s. Moreover, the parallel TCVs' respective heat event signified that the occupants' psychological thermal comfort affects their sleep quality regardless of having up-to-code building insulation methods.

4.3. Influence of Mechanical Ventilation on Thermal Comfort and Sleep Quality Evaluations

The results that include users of mechanical ventilation showed that all TCVs were increased and the majority of TSVs decreased. Similar results were pointed out by [124], who investigated the relationship between thermal history and indoor comfort. They revealed that air conditioning increased the TSVs. Furthermore, these increases in TCVs represented improvements in favour of insulated buildings, particularly during the VHD_{33}s, which had the highest heat stress among heat thresholds.

A similar improvement in favour of insulated buildings was seen in the majority of the SQVs, notably in VHD_{33}s, when the users of mechanical ventilation were excluded.

Thus, it was ascertained that mechanical ventilation was a temporary and ineffective tool to enhance sleep environments and sleep quality in uninsulated buildings. Particularly, it was insufficient to provide an optimal thermal environment for sleep within the extreme conditions of VHD_{33}s in uninsulated buildings.

Given that both TCVs and SQVs were improved within the results not involving users of mechanical ventilation compared to those involving users of mechanical ventilation, it was possible to point out that the utilization of mechanical ventilation, such as air conditioners in a pre-sleep period, did not contribute to thermal comfort and sleep quality of occupants. The authors of [139] also reported that using air conditioning before going to bed did not improve subjects' sleep quality. The authors of [140] found that naturally ventilated bedrooms provide a better sleep environment than air-conditioned bedrooms.

4.4. Management of Existing and Impending Heat Stress Events in Ankara to Address Human Sleep Quality in an Urban Context

In light of the existing literature and the outcomes of this study, several strategies can be generated to ensure sleep quality standards by managing current and impending heat stress risks in Ankara, as delineated in Figure 12. First of all, a comprehensive base should be created by detecting the local vulnerability in terms of climatic risk factors, built environment, and occupants to recognize and comprehend the local needs. Thus, local, human-centred, and innovative solutions can be integrated with that solid knowledge base to improve occupants' quality of life and safety as urban fabrics continue to warm up in an era of climate change.

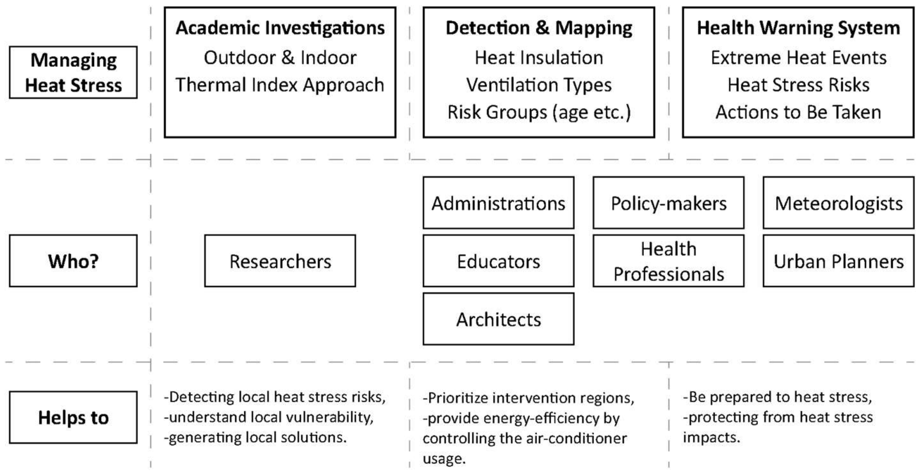

Figure 12. Diagram of step-by-step management of heat stress events in Ankara with an interdisciplinary approach.

Within the research and development process of the local base, the utilization of bottom-up approaches can elaborate the understanding of local vulnerability. For instance, considering both exterior and interior environments are effective on human health [141,142], both outdoor and indoor meteorological factors should be addressed in investigating indoor thermal comfort and sleep quality, contrary to the previous studies that used only indoor thermal parameters [6,15–18,68,82,86,91]. However, individual meteorological factors are insufficient to describe the relationship between the human body and thermal environments [133,143]. Therefore, the assessments of outdoor and indoor thermal parameters should be supported by a thermal index approach to explore the influence of these climatic factors on the human body through bidirectional heat fluxes between the human body and the environment.

In addition to bottom-up academic investigation methods, an interdisciplinary approach can advance the development of local knowledge base efforts. Within this interdisciplinary approach, professionals in the decision-making, administration, urban planning, architecture, education, and health fields can work together to create a local inventory of vulnerable construction typologies. It is possible to multiply the perspectives of vulnerability for local risk management. However, given the focus and results of this research, the investigation of vulnerability in terms of heat insulation, ventilation types, and risk groups of dwellers gains prominence. Detection and mapping of the number, age, and locations of insulated and uninsulated buildings can help prioritize the urgent urban areas for the urban transformation processes in relation to existing and future microclimatic vulnerability.

Similarly, identifying ventilation types, i.e., natural or mechanical ventilation, can help to generate energy-efficient and thermally comfortable built environments concerning outdoor-indoor transitions. As an example, the usage of air conditioners is gradually increasing worldwide due to higher air temperatures [144]. Nonetheless, as revealed by this study, the utilization of mechanical ventilation, such as air conditioners, did not improve the thermal comfort or sleep quality of the occupants. In fact, air conditioners do not benefit people, but they damage the indoors and outdoors by releasing CO_2 and waste heat [145–147]. More critically, air conditioning can increase the vulnerability of human health to heat stress [148]. Thus, considering the costs and benefits of air conditioning, controlling the usage amount of air conditioning with regulations and education, and providing and encouraging alternative environmental solutions based on scientific knowledge can be the initial interferences of administrations.

In addition to the detection of insulation and ventilation facilities in built environments, the vulnerability of dwellers should be determined to produce particular and efficient solutions to heat stress risks. For instance, as one of the most important findings of this study and existing literature, aged people tend to evaluate their thermal comfort as comfortable even though their physiological results indicate the opposite conditions. Nevertheless, even though older adults perceive warmer environments as comfortable, their bodies remain exposed to heat stress, as verified by the lower SQVs of pre-2000 buildings in extreme conditions of VHD_{33}s. Therefore, increasing local heat stress is still a risk factor for the elderly, regardless of their psychological preferences. Within this scope, detecting vulnerable age groups can contribute to handling the heat stress risks factors associated with the elderly. For instance, elderly adults may not be able, or wish, to effectively address certain risk factors pertaining to heat exposure given the aforementioned factors regarding habituation and accustomization patterns. Hence, initiating a health warning system [149] for Ankara can be helpful in informing about the upcoming local extreme heat events, their risks to specific groups, and actions to be taken. Furthermore, considering that heat stress endangers more extensive risk groups in terms of age, sex, socioeconomic factors, living environment, and diseases [150], the application of a health warning system constitutes an urgency to mitigate the impacts of current and impending local extreme heat events in Ankara.

4.5. Limitations and Future Studies

Within the undertaken study, the thermal comfort and sleep quality of occupants were evaluated against local heat stress events for Ankara, utilizing the thermal index approach within both outdoor and indoor contexts. Moreover, the two-tiered approach, including both physiological and psychological measurements, was used in this study. The thermal comfort of occupants was evaluated through both physiological and psychological data. For the physiological evaluations of thermal comfort, a subsequent study with additional equipment would be beneficial, including with regards to supplementary in-situ globe temperature measurements. Also, the sleep quality results were based only on subjects' psychological evaluations. Due to the prevailing COVID-19 pandemic during the study, the research was constrained in its ability to include physiological sleep quality assessments, owing to the need to prioritize COVID-19 precautions and ensure participants' well-being. Thus, there is the opportunity to further evaluate sleep quality in a subsequent study where such physiological aspects are considered during local heat events in Ankara.

Even though thermal comfort and sleep are individual practices eventually, exploring the local influencing factors can help advance the understanding of them, which is conducive to improving these personal experiences in a social context. Within this scope, further examination of the following issues can elaborate on the current effort to improve human life. Firstly, considering the mutual interaction of sleep and diet [151,152], complementing the undertaken methodology with evaluations of dietary habits, including meals, drinks, and nutrition intakes, is recommended for future studies. Secondly, the inclusion of longer-term thermal history in psychological evaluations in terms of climatic background and residence time can facilitate comprehending the impact of thermal adaptation, expectation, and comfort of occupants [123,153]. Moreover, regarding the trend of increasing summer days in Turkey [154], discovering the thermal comfort and sleep quality within a more extended period and performing the present methodology in different seasons to compare the impacts of extreme conditions are suggested for future studies. Additionally, detecting the extreme cold thresholds of Ankara and investigating the thermal comfort and sleep quality under cold thresholds can enhance the existing knowledge on local vulnerability towards global climatic risk factors.

In addition, the foundations of this two-tiered methodology can serve as a framework for evaluating the relationship between thermal comfort and sleep quality in various settings. Further studies can extend the application of this methodology to diverse geographic regions beyond Ankara to contribute to a more comprehensive understanding of the impact of local conditions on thermal comfort and sleep quality.

5. Concluding Remarks

This study aimed to investigate the occupants' thermal comfort and sleep quality depending on the local outdoor heat stress events by comparing the indoor conditions of insulated and uninsulated buildings. The two-tiered approach, including the results of the 99 interviews and physiological measurements, demonstrated the various impacts of three outdoor heat events, i.e., typical summer days, very hot days, and heat wave events, on the thermal comfort and sleep quality of occupants. These impacts can be disclosed in three main implications, as summarized in Table 10.

Firstly, there were unexpected higher thermal comfort and sleep quality evaluations in uninsulated buildings than in insulated ones during typical summer day and heat wave events, whereas the indoor heat stress was higher in uninsulated buildings. These results showed that only psychological evaluations depending on meteorological factors are insufficient in understanding the impact of the thermal environment on the human body. Therefore, the extended investigation of thermal comfort and sleep quality in Ankara through the utilization of the physiologically equivalent temperature thermal index in addition to meteorological variables produced a new effective means to approach outdoor and indoor heat stress and their interrelationships with the human biometeorological system.

Secondly, the higher thermal comfort and sleep quality evaluations in insulated buildings than in uninsulated ones within the highest outdoor and indoor heat stress conditions of very hot days delineated the integral role of insulation. However, the higher pre-sleep indoor physiologically equivalent temperatures in comparison to outdoors indicated that the higher diurnal outdoor heat stress retained its impact over the indoors in the nocturnal period in both insulated and uninsulated buildings. Thus, assuming psychological thermal comfort and sleep quality is optimal in up-to-code insulated buildings, and relying on the existing design standards can be misleading. In addition, demographic, individual, and environmental factors, including age, bed insulation, thermal history, and ventilation type, can still affect these insulated indoor environments, which are considered comfortable. Hence, it is necessary to review and revise the design standards with respect to local needs and the vulnerability of occupants and indoors to growing heat stress risk.

Table 10. Summary of the pre-sleep outdoor and indoor thermal heat stress, occupants' sleeping conditions and their relationship with psychological thermal comfort, and sleep quality evaluations.

			Typical Summer Day		**Very Hot Day**		**Heat Wave Event**	
Outdoor		Physiologically Equivalent Temperature	14.4 °C		19.0 °C		17.2 °C	
Indoor—Uninsulated Residential Settings	Pre-sleep Physiological Evaluations	Physiologically Equivalent Temperature	28.7 °C		30.3 °C		29.5 °C	
	Pre-sleep Psychological Evaluations	Users of mechanical Ventilation	Inclusive	Noninclusive	Inclusive	Noninclusive	Inclusive	Noninclusive
		Overall Thermal Comfort Sensation Vote	1.41	1.47	0.20	0.29	−0.31	−0.15
		How was your sleep yesterday?	3.76	3.67	3.60	3.57	3.69	3.85
	Influencing Factors	Average Age	43.8		48.4		43.9	
		Mean Sleepwear Level	2.71		2.27		1.88	
		Mean Bed Covering Level	3.24		2.53		2.40	
		Being Outdoor Ratio (24 h)	82.4%		73.3%		100.0%	
		Window Opening Ratio	29.4%		53.3%		56.3%	
Indoor—Insulated Residential Settings	Pre-sleep Physiological Evaluations	Physiologically Equivalent Temperature	27.4 °C		28.7 °C		28.0 °C	
	Pre-sleep Psychological Evaluations	Average Age	31.8		32.0		31.8	
		Users of mechanical Ventilation	Inclusive	Noninclusive	Inclusive	Noninclusive	Inclusive	Noninclusive
		Overall Thermal Comfort Sensation Vote	1.11	1.17	0.63	0.86	−0.69	−0.33
		How was your sleep yesterday?	3.68	3.67	3.63	3.79	3.00	3.00
	Influencing Factors	Average Age	31.8		32.0		31.8	
		Mean Sleepwear Level	2.05		2.13		1.88	
		Mean Bed Covering Level	2.58		2.25		2.06	
		Being Outdoor Ratio (24 h)	73.7%		68.8%		68.8%	
		Window Opening Ratio	47.4%		75.0%		75.0%	

Finally, substantial improvements in thermal comfort and sleep quality evaluations were recognized when mechanical ventilation users were excluded. These findings confirmed that singular artificial ventilation is an insufficient and ineffective way to create thermally comfortable sleep environments and improve sleep quality within residential dwellings. Notably, the majority of these improvements were in favour of insulated buildings, particularly in the highest heat stress level of very hot days. These results highlighted the profound vulnerability of widely used uninsulated indoors to climatic risk factors. Thus, instead of individual, temporary, and detrimental mechanical ventilation usage, locally adapted design standards and energy management strategies should provide permanent solutions for indoor thermal comfort and effective sleep environments.

These implications delineated that analysing both outdoor and indoor conditions and their bidirectional interactions incorporated with the thermal index approach provided an effective means to better evaluate occupants' heat stress exposure, overall thermal comfort, and sleep quality. Notably, the findings of this study accentuate the vulnerability of indoor spaces within still-occupied uninsulated buildings towards extreme outdoor heat stress events in Ankara's hot and dry summers. In addition, when considering the accelerating urbanization rate in Ankara and its concomitant risk factors, the need for mitigative, protective, and warning strategies and applications becomes inevasible. Within this context, and moreover, within an era of climate change, with increasing numbers of extreme heat events, this study emphasizes the importance of interdisciplinary approaches and methodologies: more specifically, those that bridge a better understanding of maintaining urban wholesome health standards and effective thermal sensitive architectural and urban planning approaches, and just as importantly, to moreover delineate new mechanisms within both the education of these fundamental practices and risk factors upon policymakers and the urban inhabitants themselves. Only in this way is it suggested that contemporary cities, witnessing clear symptoms of rapid urbanization, as is the case of Ankara, can ensure the encompassing of long-term urban safety, comfort, and overall well-being in an era prone to further climatic aggravations.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/atmos14091407/s1. Questionnaire Sheet S1: Questionnaire Sheet—Investigation of the Relationship between Outdoor Heat Events and Sleep Quality in Ankara.

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Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: All the data and materials used in this research are presented in the figures and tables. Further information is available from the corresponding author upon reasonable request.

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Abbreviations

AMS	Ankara Meteorological Station
ASV	Air Velocity Sensation Vote
CCDI	Climate Change Detection Indices
CTIS	Climate-Tourism/Transfer-Information-Scheme
EBM	Energy Balance Model
HSV	Humidity Sensation Vote
HWE31	Heat Wave Event
KG	Köppen–Geiger
KHS	Kestrel Heat Stress
MEMI	Munich Energy-Balance Model for Individuals
MRT	Mean Radiant Temperature (°C)
MRTIn	Indoor Mean Radiant Temperature (°C)
MRT20	Tropical Nights
Oct	Octas
PET	Physiologically Equivalent Temperature (°C)
PETIn	Indoor Physiologically Equivalent Temperature (°C)
PETInPRE	Indoor Physiologically Equivalent Temperature in Pre-2000 Buildings (°C)
PETInPOST	Indoor Physiologically Equivalent Temperature in Post-2000 Buildings (°C)
PETOut	Outdoor Physiologically Equivalent Temperature (°C)
PS	Physiological Stress
REM	Rapid Eye Movement
RHIn	Indoor Relative Humidity (%)
RHInPRE	Indoor Relative Humidity in Pre-2000 Buildings (%)
RHInPOST	Indoor Relative Humidity in Post-2000 Buildings (%)
RHOut	Outdoor Relative Humidity (%)
SQV	Sleep Quality Vote/Ratio
TaIn	Indoor Air Temperature (°C)
TaInPRE	Indoor Air Temperature in Pre-2000 Buildings (°C)
TaInPOST	Indoor Air Temperature in Post-2000 Buildings (°C)
TaOut	Outdoor Air Temperature (°C)
Tcr	Core Body Temperature
TCV	Thermal Comfort Vote
TgIn	Indoor Globe Temperature (°C)
TSD25	Typical Summer Day
Tsk	Skin Temperature
TSV	Thermal Sensation Vote
TÜBİTAK	Turkish National Scientific and Technological Research Council
VIn	Indoor Air Velocity (M/S)
VOut	Outdoor Wind Speed (M/S)
VHD33	Very Hot Day

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