



# Thermal sensation and indices in the urban outdoor hot Mediterranean environment of Cyprus

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## Abstract

Several thermal indices have been proposed for quantification of various aspects of the thermal environment. Their applicability however is a methodological conundrum. The aim of the present study (part of the Biometeorological Aspect of Thermal environment and Health (BeAT Heat) project) was to assess the outdoor thermal environment using data on thermal sensation. In particular, the study tried to identify the thermal index that best simulates thermal sensation in the temperate and dry Mediterranean climate of Cyprus. Field surveys were conducted in summer 2019 in public urban spaces of five districts in Cyprus. These surveys involved monitoring of micrometeorological conditions and conducting questionnaire-based interviews with pedestrians in order to collect data on actual thermal sensation (ATS), demographics, and physiological and psychological variables. The study participants, using a predefined thermal sensation scale, reported their ATS. Variations of thermal sensation across the participants were studied in relation to the outdoor thermal environment and to physiological factors. ATS was compared with simulated thermal sensation (STS) produced by operationally used thermal indices under matching weather conditions, i.e., Heat Index, Humidex, and Wet-Bulb Globe Temperature. Physiologically Equivalent Temperature was additionally considered. All indices showed low predictability of ATS. The thermal index that performed best to the temperate and dry Mediterranean climate of Cyprus was the Heat Index using an assessment scale modified for the Mediterranean climate.

## 1 Introduction

Assessment of thermal conditions in the outdoor urban environment helps address economic and social issues and challenges including tourism (Rutty and Scott 2013), planning of cities and urban design (Tseliou and Tsiros 2016), energy conservation (Li et al. 2019), and public health (Gasparrini et al. 2015). Thermal conditions are the integrated product of environmental factors including air temperature, relative humidity, solar radiation, and wind velocity. People's assessment of

thermal conditions, i.e., thermal sensation, is subjective and affected by personal factors as well (Nikolopoulou and Lykoudis 2006; Pantavou et al. 2013b) including clothing insulation and activity.

Several models have been suggested to assess and quantify thermal environment based on thermal sensation or thermal stress. Around 165 thermal indices have been developed since the 1950s (Yaglou and Minard 1957; de Freitas and Grigorieva 2017), but their applicability is methodologically challenging. Indices have been classified based on their rationale, intended use (e.g., indoor or outdoor), type, and quality (de Freitas and Grigorieva 2015; Coccolo et al. 2016), and their performance was evaluated in order to find the most suitable for a given application (Pantavou et al. 2013a; Coccolo et al. 2016). The assessment scales of universal indices have been calibrated to improve their performance in specific climates. Thus, new thresholds of thermal sensation and comfort were defined based on how individuals in local settings reported thermal sensation (Lin and Matzarakis 2008; Pantavou et al. 2014; Pantavou et al. 2018).

Studies on subjective thermal sensation considering in situ thermal conditions have been conducted worldwide (Potchter

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et al. 2018). Many of them aimed to modify thermal indices' scales for different climates, e.g., tropical (Aw) (Monteiro and Alucci 2006; da Silva Hirashima et al. 2018; Krüger et al. 2017), oceanic (Cfb) (da Silva Hirashima et al. 2018; Krüger et al. 2017), subtropical (Cwa) (Lin and Matzarakis 2008; Lai et al. 2014), Mediterranean (Csa) (Pantavou et al. 2013b), and continental (Dwa) (Lai et al. 2014), while some focused only on determining neutral class (da Silva and de Alvarez 2015; Elnabawi et al. 2016). Physiologically Equivalent Temperature (PET) was probably the most commonly calibrated index in the published literature (Potchter et al. 2018). Several calibration methods have been used including linear (Pantavou et al. 2014; Krüger et al. 2017), cubic (Pantavou et al. 2014), and ordinal (da Silva Hirashima et al. 2018) regression, discriminate analysis (Cohen et al. 2013), probit analysis (Pantavou et al. 2014), or based on unacceptability votes (Lin and Matzarakis 2008; Pantavou et al. 2013b; Tseliou et al. 2017). The applicability of the indices has also been examined by comparing indices' simulations with the results of empirical field surveys (Monteiro and Alucci 2006; Pantavou et al. 2013a; Pantavou et al. 2014).

Field surveys in the Mediterranean climate, i.e., Lisbon, Portugal (Oliveira and Andrade 2007); Tel Aviv, Israel (Cohen et al. 2013); Athens (Nikolopoulou 2004; Pantavou et al. 2013b; Pantavou et al. 2013a; Tseliou and Tsiros 2016) and Crete, Greece (Tsitoura et al. 2014); and Rome, Italy (Salata et al. 2016) followed different approaches to evaluate thermal sensation. One of these studies (Pantavou et al. 2013a) examined the suitability of a large number of indices in urban, outdoor places resulting in a maximum rate of successful predictions of 57.9%. Moreover, in that study, the majority of indices predicted successfully about 35% of the actual thermal sensation reported by 1706 respondents.

Three studies modified the thermal indices' scales for the Mediterranean climate (Cohen et al. 2013; Pantavou et al. 2014; Tseliou and Tsiros 2016). The research teams of these studies primarily focused on the calibration of the PET index and the Universal Thermal Climate Index (UTCI). In the study of Pantavou et al. (2014), several indices were calibrated based on a 7-point thermal sensation scale. The use of the modified scales improved the maximum rate of correct predictions by 5.7% (63.6 rather than 57.9%) and the mean predictability by 7.1% (42.1 rather than 35%) compared with the original scales. The boundaries of the assessment scales varied between comparable studies (Cohen et al. 2013; Pantavou et al. 2014), probably because of different methods of calibration, of psychological parameters considered (Nikolopoulou and Steemers 2003), and/or of local microclimatic features.

Climatic characteristics and local environmental conditions are essential to assessing thermal sensation (Pantavou et al. 2018). Cyprus is characterized by a temperate and dry Mediterranean climate with six, hot and dry months, during which the average bright sunshine per day is 11.5 h (CDM-

Cyprus Department of Meteorology 2019). This particular feature of the Mediterranean climate needs to be considered in terms of the ability of thermal indices to predict thermal sensation in outdoor environments. In addition, given global climate change and rise of ambient temperature, there are also concerns over the public health consequences of thermal burden and the demand for action is increasing. The aim of the present study was to assess the outdoor thermal environment in Cyprus based on thermal sensation and focusing on the performance of appropriate indices used operationally in weather services worldwide. Since thermal stimuli differ across locations and cultures, findings in a new setting like that of Cyprus contribute to the expansion of the knowledge base and to comparisons with other studies both in similar and in different climates. Moreover, this study adopts a different approach compared with previous research in the Mediterranean climate: the performance of the indices is assessed based on a nine-point thermal sensation scale.

## 2 Methodology

### 2.1 Study area

The study was conducted in the Republic of Cyprus, a country on an island of the Eastern Mediterranean region and a very popular tourist destination. Cyprus is closer to the Asian continent but belongs historically and culturally to Europe and is nowadays a member state of the European Union. The coastal zone (2 km inland from the coastline) represents 23% of the island (Zachariadis 2012). There are two mountain ranges. The largest is in the southwest of the island (Troodos, highest peak Mount Olympus at 1951 m) and the second one (Pentadaktylos, highest peak Mount Kyparissovouno at 1024 m) is in the northern coast of the island.

Cyprus has a temperate and dry Mediterranean climate (CDM 2019) including the Csa and BSh types of the Köppen-Geiger climate classification (Kottek et al. 2006). Summers are hot and dry lasting from mid-May to mid-September. The sky is almost cloudless and the rainfall negligible. Several climatic characteristics of Cyprus are presented in Table 1. The temperature lowers with altitude by about 5 °C/km. The difference between day maximum and night minimum temperature is between 9 and 12 °C reaching 16 °C in the central plain. In July and August, the mean daily temperature across the country ranges between 29 and 22 °C, respectively, and the mean maximum temperature between 36 and 27 °C, respectively. The highest recorded temperature was 45.6 °C (1st August 2010, Athalassa) (CDM 2019).

The Republic of Cyprus is divided in five administrative districts, i.e., Nicosia, Limassol, Larnaca, Paphos, and Famagusta. Each district has a large city that bears the same name. Nicosia city, the capital of the country, lies in the center

**Table 1** Climatic characteristics of Cyprus (CDM 2019)

Temperature decrease with altitude	5 °C/km	
Diurnal temperature range	9–12 °C (reaching 16 °C in the central plain)	
Maximum recorded temperature	45.6 °C (1st August 2010, Athalassa)	
	Plains	Troodos
Mean daily temperature July–August	29 °C	22 °C
Mean maximum temperature July–August	36 °C	27 °C

of the island. Large coastal cities include Limassol, Larnaca, and Paphos. Field surveys were carried out in the largest city of each of the four districts of the Republic of Cyprus, i.e., Nicosia, Limassol, Larnaca, Paphos, and in a popular summer resort of the country, Protaras town. In order to collect data for a wider range of micrometeorological conditions, apart from city centers, the field surveys were also conducted in Kakopetria village (Nicosia district) at the foot hills of Troodos mountain and in Poli Chrysochous (Paphos district), a village on the northern coast (Fig. 1).

## 2.2 Data collection

The field surveys were conducted in the context of the Biometeorological Aspect of Thermal environment and Health (BeAT Heat) project. BeAT Heat is being conducted in Cyprus and aims to assess the potential health effects of thermal environment using an integrated approach (Pantavou et al. 2019). The surveys were carried out between 28th June and 4th July 2019 and on 6th July 2019 including hours from morning to night. They included monitoring of

micrometeorological conditions in outdoor, urban public places (i.e., squares, promenade streets, and streets) and interviews of pedestrians based on a structured questionnaire. The protocol and the questionnaire of the field surveys were approved by the Cyprus National Bioethics Committee (EEBE/EII2018/48).

### 2.2.1 In situ measurements

A mobile weather station equipped with a Hygromer HT-1 (HC2A-S3) sensor (accuracy  $\pm 0.8\%$  RH,  $\pm 0.1^\circ\text{K}$ ) with a non-ventilated radiation shield of aluminum measured air temperature ( $T_{\text{air}}$ , °C) and relative humidity (RH, %). The sensor was mounted on a mobile tripod at the height of 1.1 m above the ground. This is the average height of the center of a human body (Mayer and Höppe 1987; Johansson et al. 2014) and was selected based on previous studies, in order to adhere to a standardized monitoring method (Pantavou et al. 2013b; Johansson et al. 2014). The data were recorded at 30-s intervals and stored as 1-min averages on a CR1000 Campbell Scientific data logger.



**Fig. 1** Sites of field surveys in the context of the BeAT Heat project in the Republic of Cyprus (Google Earth, Image Landsat/Copernicus, Data SIO, NOAA, U.S. Navy, NGA, GEBCO)

### 2.2.2 Questionnaire-based interviews

Questionnaire-based interviews with people visiting the monitoring sites were conducted using tablet computers. All people present at those sites on the day of the field survey were eligible to participate. Study participants were orally informed about the purpose of the survey and gave their verbal informed consent. The questionnaire included items on participants' demographics (i.e., gender, age, city of residence), on physiological parameters (i.e., clothing description, activity, exposure time and history, health condition, medical history), and on psychological variables (i.e., visit purpose, perceived risk, familiarity, trust to state institutions). Clothing insulation (Iclo, clo) was estimated according to ISO 9920 (2007) by participants' clothing description. The participants were also asked to assess and report their thermal sensation (actual thermal sensation (ATS)) and thermal comfort (TC). ATS was reported on the nine-point scale suggested in ISO 10551 (2001), i.e., - 4, very cold; - 3, cold; - 2, cool; - 1, slightly cool; 0, neutral; + 1, slightly warm; + 2, warm; + 3, hot; and + 4, very hot. TC was reported on a 5-point scale (Table 2).

**Table 2** Items of the questionnaire used in the field surveys

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How long have you been in this place? (*exposure time*):  
 < 5 min  5 to 15 min  15 to 30 min  30 min to 1 h  >1 h

Where were you during the last half hour? (*exposure history*):  
 outdoors  indoors without AC  indoors with AC  vehicle without AC  vehicle with AC

Reason to be in this place: (*visit purpose*):  
 rest  entertainment  work  passing by

How do you feel at this precise moment? (*actual thermal sensation, ATS*):  
 very cold  cold  cool  slightly cool  neutral  slightly warm  warm  hot  very hot

Do you find this (*thermal comfort, TC*):  
 comfortable  slightly uncomfortable  uncomfortable  very uncomfortable  extremely uncomfortable?

Do you think that the thermal environment can possibly be dangerous to your health? (*perceived risk*):  
 not possible  barely possible  average  fairly possible  totally possible

Assuming that you have no source of information, do you think you can know when a heat wave occurs in a timely manner? (*familiarity*):  
 not possible  barely possible  average  fairly possible  totally possible

To what degree do you place trust to the state institutions to deal with heat waves? (*trust to state institutions*):  
 not trust at all  barely trust  average  fairly trust  completely trust

Today your health condition is: (*health condition*):  
 as usual  better than usual  worse than usual

Do you have any chronic condition like (*medical history*):  
 respiratory (including asthma)  cardiovascular?  none

Age:  
 ≤12  13–17  18–24  25–34  35–44  45–54  55–64  >65

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Abbreviation: AC, air-conditioning

### 2.3 Thermal indices

The following thermal indices were considered in this study: Heat Index (HI, °C) (Steadman 1979), Humidex (HU, °C) (Masterson and Richardson 1979), Wet-Bulb Globe Temperature (WBGT, °C) (Yaglou and Minard 1957), and the Physiologically Equivalent Temperature (PET, °C). HI, HU, and WBGT are operational and used by weather services around the globe for the assessment of thermal burden in hot environments. In particular, HI is used by the National Weather Service of America (NOAA 2019) and the National Observatory of Athens, Greece (NOA 2019). HU is currently used by the Canadian government in their weather bulletins released to the public (Government of Canada 2019). WBGT is used by the Bureau of Meteorology of the Australian Government (Bureau of Meteorology 2019). PET (Mayer and Höppe 1987; Höppe 1999) is a widely used index in studies on outdoor thermal sensation (Potchter et al. 2018). The thermal assessment scale of PET is derived from the model for human energy balance MEMI (Munich energy balance for individuals) and can be applied to the changing conditions of an outdoor environment.

Appendixes 1 include the original and the modified scales of HI, HU, WBGT, and PET for the Mediterranean climate assessment (Tables 8, 9, 10 and 11).

### 2.4 Data processing

Meteorological and questionnaire data were checked for values that did not make sense and for possible outliers.

HI, HU, and WBGT were estimated using versions of equations that can be easily estimated by the available weather station data. The equations of the indices are included in Appendix 2.

PET was estimated using Rayman software (Matzarakis et al. 2007; Matzarakis et al. 2010). For the needs of this study, PET was estimated based on date, time, latitude, longitude, altitude, time zone, Tair, and RH. The aim was to estimate PET by the same variables used to estimate HI, HU, and WBGT. Clothing insulation was set to 0.4 clo, activity to 95 W/m<sup>2</sup> (corresponding to a standing person (ISO 8996 2004)), and personal data were set to those of a 35-year-old male of 1.75 m height and 75 kg weight.

One-minute averages of Tair and RH stored in the mobile weather station were used to estimate HI, HU, WBGT, and PET. However, the time needed to complete an interview was 5 min. Therefore, 5-min average of HI, HU, WBGT, PET, and of the measured variables Tair and RH were calculated to match the questionnaire data.

Simulated thermal sensation (STS) was estimated by the values of the four indices and their classification according to the respective original scales and the Mediterranean-wise modified climate assessment scales (Tables 8, 9, 10 and 11).

## 2.5 Statistical analysis

Statistical analyses were performed in Stata 14.1 (StataCorp LP, College Station, Texas, USA). A  $p$  value less than 0.05 indicates statistical significance.

### 2.5.1 Descriptive analysis on participants' characteristics and thermal environment

Continuous variables, e.g., Tair, RH, HI, HU, WBGT, and PET were described using mean, median values, standard deviation, and interquartile range. Categorical variables, i.e., questionnaire items, were described with frequencies and percentiles.

### 2.5.2 Analysis on actual thermal sensation

Chi-squared tests were used to explore the association between ATS and other categorical variables of the questionnaire. Analysis of variance (one-way ANOVA) and linear regression were used to examine the association between ATS and continuous variables, i.e., Tair, RH, HI, HU, WBGT, and PET. ATS was treated as a continuous dependent variable in linear regression models.

### 2.5.3 Analysis on the performance of thermal indices

The performance of the four thermal indices was evaluated based on the comparison of STS with ATS. Four criteria were used to evaluate indices' performance (Monteiro and Alucci 2006; Pantavou et al. 2013a):

- The strength of association between indices' values and ATS, assessed by Spearman correlation coefficient,
- The strength of ordinal association between STS and ATS validated by Goodman and Kruskal's gamma measure of association,
- The total percentage of correct predictions, and
- The percentage of correct predictions per ATS class based on cross-tabulation analysis.

Criterion  $a$  estimates the correlation between HI, HU, WBGT, PET, and ATS while criterion  $b$  estimates the correlation between STS and ATS. Both criteria show how indices' values or classes vary in relation to ATS variations. Criteria  $c$  and  $d$  estimate the percentage of correct predictions verifying indices' good performance, overall and per class of ATS.

ATS was adjusted to the assessment scale of HI, HU, and WBGT, i.e., the extreme classes of ATS (+3, +4 and -3, -4) were collapsed into classes +3 or -3 only when the modified assessment scales for the Mediterranean were considered. Similar, ATS was adjusted to the assessment scale of PET in the case of the modified scale for Athens.

Estimates from statistical criteria  $a$ ,  $b$ , and  $c$  were normalized using the maximum value per criterion as reference (each value is replaced by its ratio to the respective maximum value) and summed to produce an objective, aggregate measure of the indices' overall performance.

In order to reduce variations of ATS under the same thermal conditions, we compared the indices with ATS in terms of thermal unacceptability. The percentage (%) of thermally "unacceptable" responses was estimated for each 1 °C of the indices. Unacceptability was defined considering ATS (the positive classes of the 9-point scale, +1 to +4) and TC reported by the participants (classes "slightly uncomfortable," "uncomfortable," "very uncomfortable," "extremely uncomfortable"). ASHRAE Standard 55 (American Society of Heating Refrigerating and Air-Conditioning Engineers 2013) defined acceptable thermal conditions for indoor environments as the conditions which are acceptable by 90% (minimum) of the occupants or unacceptable by the 10% of the occupants. However, 20% unacceptability is used in typical applications.

## 2.6 Sample size

The minimum sample size required was estimated at 350 persons based on the 2011 census population of 840,407 (Statistical Service 2019) and assuming a 5% margin of error, a 95% level of confidence, and that 35% of the study participants would probably report the same class (warm) of the seven-point thermal sensation scale (Pantavou et al. 2013b).

## 3 Results

### 3.1 Participants' characteristics and thermal environment

We collected 824 questionnaires by 439 (54.7%) males and 364 (45.3%) females, who were residents of the Republic of Cyprus (Table 3). Their age varied from  $\leq 12$  years ( $n = 13$ , 1.6%) to  $> 65$  years ( $n = 96$ , 11.6%) with the majority falling into the age group of 18–44 years (464, 56.4%). The median value of clothing insulation that was estimated based on the description of clothing the participants wore during the interview was 0.3 clo (25 and 75% percentile 0.23 and 0.42 clo; mean  $0.3 \pm 0.1$  clo).

Most participants self-reported no medical history of respiratory or cardiovascular conditions (87.2%,  $n = 717$ ), and that on the day of the interview, their health was the usual or better than usual (90.9%,  $n = 741$ ). The majority of study participants reported that during the last half hour, they were mainly sitting ( $n = 490$ , 60%). Most study participants were at the site of the interview for more than 15 min ( $n = 550$  67.5%), and in the last half hour, they were mainly in an outdoor place ( $n =$

**Table 3** Participants' responses on demographic, physiological, and psychological variables included in the questionnaire used in the field surveys

Variable	Categories	Number	Percentage (%)
Gender	Males	439	54.7
	Females	364	45.3
Age	≤ 12	13	1.6
	13–17	84	10.2
	18–24	218	26.5
	25–34	139	16.9
	35–44	107	13.0
	45–54	97	11.8
	55–64	70	8.5
Medical history	> 65	96	11.6
	Respiratory	53	6.5
	Cardiovascular	52	6.3
Health condition	None	717	87.2
	Worse than usual	74	9.1
	As usual	646	79.3
Activity	Better than usual	95	11.6
	Lying	27	3.3
	Sitting	490	60.0
	Standing	69	8.4
Exposure time	Walking	193	23.6
	Sports	38	4.5
	< 5 min	158	19.4
	5–15 min	107	13.1
	15–30 min	95	11.7
Exposure history	30 min–1 h	115	14.1
	> 1 h	340	41.7
	Outdoors	459	56
	Indoors without AC	59	7.2
	Indoors with AC	109	13.3
Visit purpose	Vehicle without AC	49	6.0
	Vehicle with AC	144	17.5
	Rest	343	41.9
	Entertainment	205	25.0
Perceived risk	Work	194	23.7
	Passing by	77	9.4
	Not possible	61	7.4
	Barely possible	76	9.3
	Average	108	13.2
Familiarity with extreme thermal conditions	Fairly possible	316	38.6
	Totally possible	258	31.5
	Not possible	34	4.2
	Barely possible	37	4.5
	Average	84	10.2
Trust to state institutions	Fairly possible	315	38.4
	Totally possible	350	42.7
	Not trust at all	340	41.6
	Barely trust	208	25.4
	Fairly trust	227	27.7
	Completely trust	43	5.3

459, 56%), indoors, or in a vehicle without air-conditioning ( $n = 108$ , 13.2%).

Nearly two thirds of the participants visited the monitoring site for rest or entertainment ( $n = 548$ , 66.9%). About 83.3% ( $n = 682$ ) of the participants believed that the risk to their health due to the thermal environment was average to totally possible. The vast majority (91.3%,  $n = 749$ ) said that they were familiar with extreme thermal conditions. A substantial percentage of the participants (41.6%,  $n = 340$ ) stated that they did not trust state institutions to deal with extreme thermal events.

Air temperature ranged between 25.0 and 36.2 °C and relative humidity ranged between 29 and 86% (Table 4). The estimated PET (range 38.6 °C, from 21.6 to 60.2 °C) varied more than HI (range 13.6 °C, from 26 to 39.6 °C), HU (range 13 °C, from 31 and 44 °C), and WBGT (range 8.7 °C, from 26 and 34.7 °C).

### 3.2 Actual thermal sensation

ATS varied between  $-2$  (cool) and  $+4$  (very hot). The majority of responses (54.4%,  $n = 448$ ) ranged between “slightly cool” ( $-1$ ) and “slightly warm” ( $+1$ ), almost equally distributed among the three classes: slightly cool ( $-1$ ) 18.6% ( $n = 153$ ), slightly warm ( $+1$ ) 18.4% ( $n = 152$ ), and “neutral” 17.4% ( $n = 143$ ). ATS “warm” ( $+2$ ) to “very hot” ( $+4$ ) classes were reported by 262 (31.8%) participants, while 13.8% of the participants ( $n = 114$ ) reported a “cool” ( $-2$ ) thermal sensation (Table 5).

In terms of thermal comfort, the number of responses ( $n = 459$ , 56%) in the class “comfortable” was comparable with what is usually considered the comfortable range of the thermal sensation assessment scale (slightly cool to slightly warm,  $-1$ ,  $0$ , and  $+1$ ). However, the cross-tabulation of ATS and comfort feeling showed that the study participants felt uncomfortable when reporting ATS in the warm subscale ( $+1$ ,  $+2$ ,  $+3$ ,  $+4$ ) rather than in the cool subscale ( $-1$ ,  $-2$ ) ( $p < 0.001$ ) (Fig. 2).

More females reported ATS in the range of  $+1$  to  $+4$  ( $n = 193$ , 53.0%) than males (214, 48.8%) although this difference

was not significant ( $p = 0.305$ ). Warm ATS ( $+1$  to  $+4$ ) was also significantly ( $p < 0.001$ ) more prevalent among participants between 18 and 44 years old (ranged between  $n = 57$ , 53.4% and  $n = 130$ , 59.6%) than among those  $< 18$  years old ( $< 45.2\%$ ,  $n = 38$ ) or  $> 44$  years old ( $< 43.3\%$ ,  $n = 42$ ). The proportion of responses in the warm classes of the ATS scale ( $+1$  to  $+4$ ) was also significantly higher ( $p = 0.034$ ) among participants who visited the monitoring sites for work ( $n = 119$ , 61.34) than among those who visited the sites for rest, entertainment or who just passed by ( $n = 165$ , 48.1%;  $n = 92$ , 44.9%;  $n = 35$ , 45.4%). Finally, significantly ( $p = 0.005$ ) more participants ( $n = 51$ , 68.9%) whose health condition was worse than usual on the day of the interview reported ATS in the warm subscale ( $+1$  to  $+4$ ) than those whose health status was as usual ( $n = 319$ , 49.4%) or better than usual ( $n = 39$ , 41.1%).

One-way analysis of variance showed statistically significant differences between classes of ATS and Tair ( $p < 0.001$ ), RH ( $p < 0.02$ ), and all four thermal indices ( $p < 0.001$ ). Linear regression showed that the four indices do predict ATS in a statistically significantly manner ( $p < 0.001$ ) with increasing ATS when indices values become higher. The indices regression coefficients ranged between 0.03 and 0.24. Although the results of linear regression analyses were significant, the indices accounted for only 4.3% (adjusted  $R^2$  for PET) to 7.9% (adjusted  $R^2$  for HI) of the variability in ATS. Tair explained even less variability (2.8%,  $p < 0.001$ ).

### 3.3 Performance of thermal indices

The comparison of STS with ATS was based on three statistical criteria, i.e., Spearman correlation coefficient, Goodman and Kruskal’s gamma measure of association, and percentage of total correct predictions, and a qualitative criterion (Table 6). Spearman correlation coefficients ranged between 0.17 and 0.23 ( $p < 0.003$ ; average 0.2) suggesting a weak correlation of indices estimates with ATS. The ordinal association between STS and ATS was better but remained weak ( $p < 0.05$ , range 0.14–0.50; average 0.28). The percentage of correct predictions ranged

**Table 4** Mean and range of meteorological variables and thermal indices during the interviews

	Mean	Standard deviation	Median	Interquartile range	Minimum	Maximum
Tair (°C)	30.0	1.6	29.7	1.6	25.0	36.2
RH (%)	59	14	58	22	29	86
HI (°C)	32.6	2.4	32.7	2.7	26.0	39.6
HU (°C)	38.1	2.8	38.1	3.6	31.0	44.0
WBGT (°C)	30.6	1.9	30.6	2.7	26.0	34.7
PET (°C)	40.5	13.3	38.1	28.3	21.6	60.2

Abbreviations: Tair, air temperature; RH, relative humidity; HI, Heat Index; HU, Humidex, WBGT, Wet-Bulb Globe Temperature; PET, Physiologically Equivalent Temperature

**Table 5** Frequency of actual thermal sensation (*N (%)*) reported by the participants in the field surveys

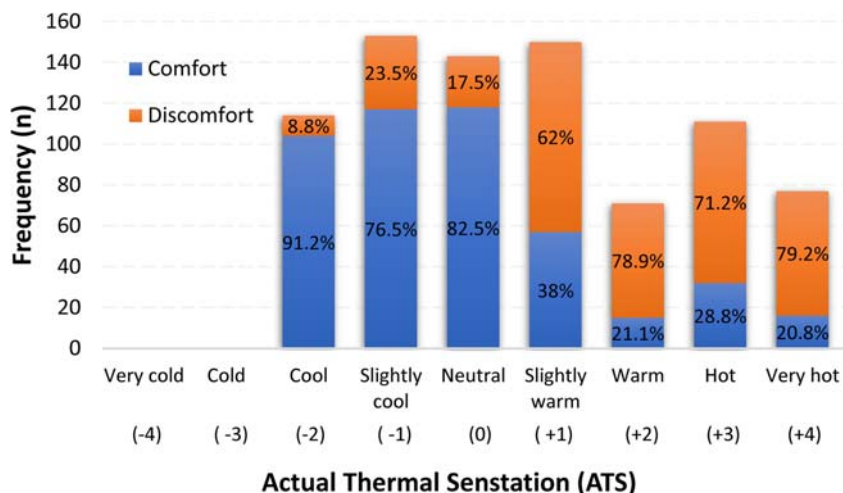
	Very cold -4	Cold -3	Cool -2	Slightly cool -1	Neutral 0	Slightly warm +1	Warm +2	Hot +3	Very hot +4
Total			114 (13.8)	153 (18.6)	143 (17.4)	152 (18.4)	71 (8.6)	112 (13.6)	79 (9.6)
Gender									
Male			67 (15.3)	83 (18.9)	75 (17.1)	86 (19.6)	33 (7.5)	54 (12.3)	41 (9.3)
Female			44 (12.1)	62 (17.0)	65 (17.9)	63 (17.3)	37 (10.2)	58 (15.9)	35 (9.6)
Age									
≤ 12			3 (23.1)	5 (38.5)	1 (7.7)	0 (0.0)	1 (7.7)	3 (23.1)	0 (0.0)
13–17			6 (7.1)	19 (22.6)	21 (25.0)	10 (11.9)	5 (6.0)	13 (15.5)	10 (11.9)
18–24			14 (6.4)	37 (17.0)	37 (17.0)	43 (19.7)	25 (11.5)	36 (16.5)	26 (11.9)
25–34			18 (13.0)	26 (18.7)	18 (13.0)	29 (20.9)	17 (12.2)	19 (13.7)	12 (8.6)
35–44			13 (12.2)	20 (18.7)	17 (15.9)	22 (20.6)	10 (9.4)	13 (12.2)	12 (11.2)
45–54			16 (16.5)	14 (14.4)	25 (25.8)	17 (17.5)	5 (5.2)	11 (11.3)	9 (9.3)
55–64			16 (22.9)	12 (17.1)	14 (20.0)	14 (20.0)	4 (53.7)	6 (8.6)	4 (5.7)
> 65			28 (29.2)	20 (20.8)	10 (10.4)	17 (17.7)	4 (4.2)	11 (11.5)	6 (6.2)
Visit purpose									
Rest			46 (13.4)	69 (20.1)	63 (18.4)	65 (18.9)	23 (6.7)	50 (14.6)	27 (7.9)
Entertainment			32 (15.6)	41 (20.0)	40 (19.5)	34 (16.6)	20 (9.8)	27 (13.2)	11 (5.4)
Work			17 (8.8)	33 (17.0)	25 (12.9)	37 (19.1)	22 (11.3)	28 (14.4)	32 (16.5)
Passing by			19 (24.7)	10 (13.0)	13 (16.9)	15 (19.5)	6 (7.8)	7 (9.1)	7 (9.1)
Health condition									
Worse than usual			4 (5.4)	8 (10.8)	11 (14.9)	13 (17.6)	7 (9.5)	15 (20.3)	16 (21.6)
As usual			84 (13.0)	130 (20.1)	113 (17.5)	119 (18.4)	61 (9.4)	85 (13.2)	54 (8.4)
Better than usual			23 (24.2)	15 (15.8)	18 (19.0)	17 (17.9)	3 (3.2)	12 (12.6)	7 (7.4)

between 6.4% (HU based on the Mediterranean scale (HUmed0) and 16.9% (PET based on the Mediterranean scale (PETmed)). PET achieved much better scores than HI, HU, and WBGT.

Mediterranean scales produced improved results than those based on the original scales. In particular, the gamma statistic was improved for all indices' predictions (range 0.22–0.50). The percentage of correct predictions was also improved except for HU (Table 6).

The normalized values of the statistical criteria were summed producing a total score for each index considering both the original assessment scales and the scales modified in previous studies for the Mediterranean climate. The total score was used for the comparison of the indices and was later assessed by the qualitative criterion, i.e., the cross-tabulation of the indices. The best total statistical score considering the original scales (2.1) was for HI. Overall, the best quality score (2.4) was estimated for HImed, WBGTmed, and

**Fig. 2** Actual thermal sensation and thermal comfort (comfort, discomfort) reported by the participants in the questionnaire-based interviews. Discomfort corresponds to classes slightly uncomfortable, uncomfortable, very uncomfortable, and extremely uncomfortable





**Table 6** Spearman’s coefficients, Goodman and Kruskal’s gamma coefficients, and percentage of correct predictions of the thermal indices Heat Index (HI), Humidex (HU), Wet-Bulb Globe Temperature (WBGT),

and Physiologically Equivalent Temperature (PET) based on the original scales and those modified for the Mediterranean climate (subscript med)

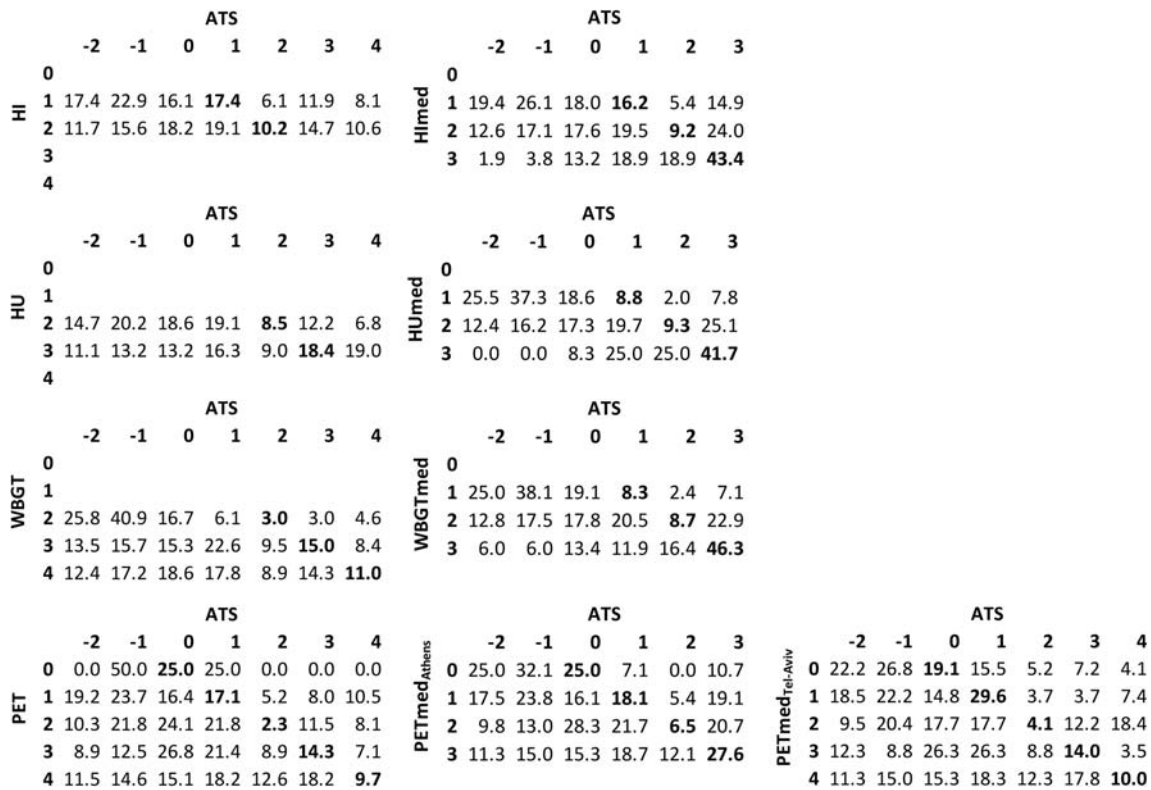
				Normalized			Total score
	Coefficients		Correct predictions (%)	Coefficients		Correct predictions (%)	
	Spearman	gamma		Spearman	gamma		
HI	0.23	0.17	12.9	1	0.34	0.76	2.1
HI <sub>med</sub>	0.23	0.31	13.1	1	0.62	0.77	2.4
HU	0.17	0.27	10.8	0.74	0.53	0.64	1.9
HU <sub>med</sub>	0.17	0.50	6.4	0.74	1	0.38	2.1
WBGT	0.17	0.14	11.6	0.76	0.27	0.69	1.7
WBGT <sub>med</sub>	0.17	0.47	11.7	0.76	0.93	0.69	2.4
PET	0.21	0.20	11.9	0.93	0.39	0.70	2.0
PET <sub>medAthens</sub>	0.21	0.22	16.9	0.93	0.44	1	2.4
PET <sub>medTel-Aviv</sub>	0.21	0.22	12.0	0.93	0.44	0.71	2.1

The results were statistically significant at the level of 0.05

PET<sub>medAthens</sub>, which could be partly attributed to the merging of classes (+ 3, + 4) in the Mediterranean assessment scales.

The qualitative criterion was the percentage of correct predictions per class of ATS. The cross-tabulation analysis (Fig. 3) showed that the evaluations of HI and HU were

classified in only two of the four classes of the original assessment scales. HI estimations were classified in the categories of caution (+ 1) and extreme caution (+ 2) (Table 8) whereas HU in the categories some discomfort (+ 2) and great discomfort, avoid exertion (+ 3) (Table 9). The WBGT performed better



**Fig. 3** Cross-tabulation of simulated thermal sensation by thermal indices Heat Index (HI), Humidex (HU), Wet-Bulb Globe Temperature (WBGT), Physiologically Equivalent Temperature (PET), and actual thermal sensation (ATS) based on the original assessment scales and the modified

scales for the Mediterranean climate (HI<sub>med</sub>, HU<sub>med</sub>, WBGT<sub>med</sub>, PET<sub>medAthens</sub>, PET<sub>medTel-Aviv</sub>). Each row sums to 100%. The correct predictions are in bold

than HI and HU, indicating three classes (+ 2 to + 4) of recommendations; unacclimatized (+ 2), all persons should be curtailed (+ 3), and all training should be stopped (+ 4) (Table 10). The evaluations of PET produced the neutral class and all classes of the warm assessment subscale, i.e., slightly warm, warm, hot, and very hot (Table 11). The number of predicted classes for HI, HU, and WBGT increased when the modified scales were used. HI<sub>med</sub> and HU<sub>med</sub> produced three classes (+ 1 to + 3) of the assessment scale instead of the original two (+ 1, + 2) for HI and (+ 2, + 3) for HU, while the WBGT<sub>med</sub> additionally simulated the class + 1. The number of correct predictions for PET<sub>med</sub><sub>Athens</sub> and PET<sub>med</sub><sub>Tel-Aviv</sub> were higher than for the original PET scale.

Considering indices' simulations based on the original assessment scales, HI and PET seem to perform better. Overall, HI<sub>med</sub> showed the best applicability with the highest statistical score (2.4), the highest percentage of correct predictions, and by producing the thermal sensation classes, + 1, + 2 and + 3. PET simulations, on the other hand, produced an overall statistical score 2.0 (about the same with that of HI, 2.1; Table 6) but also predicted all degrees of thermal sensation. Moreover, the maximum percentage of correct predictions per degree was about the same with HI (17.4 over 17.1 of PET; Fig. 3).

Even under the same thermal conditions, ATS may vary among individuals. To smooth out these variations, indices' values were binned and compared with ATS and TC. Figure 4 shows the percentage of responses in the range of unacceptable thermal conditions in terms of ATS and TC for 1 °C interval of HI, HU, and WBGT. The high range of PET (22–60 °C) produced great dispersion in the number of responses for each 1 °C interval, thus we considered a binning interval of 2 °C. The unacceptability range of ATS was defined as the classes + 1 to + 4 of the ATS assessment scale, by combining the concurrent ATS and TC responses (Fig. 1). The unacceptability range for TC included all classes of uncomfortable, i.e., slightly uncomfortable, uncomfortable, very uncomfortable, extremely uncomfortable. Since 20% unacceptability is considered to define the neutral or comfort range (Lin and Matzarakis 2008; Cohen et al. 2013), the research team adopted unacceptability limits of 30, 50, 70, and 90% to additionally examine whether HI, HU, WBGT, and PET scales fit to our data. Table 7 shows the indices' values for each unacceptability limit. The limits derived from the responses of TC were higher than ATS. This was expected since there were people feeling comfortable in a warm thermal sensation (Fig. 1).

The values of HI, HU, and WBGT corresponding to unacceptability limits for ATS successfully fell into the classes of each index's Mediterranean assessment scale (Tables 8, 9 and 10), i.e., 30% to + 1, 50% to + 2, 70% to + 3, and 90% to + 4. Considering the original scales, HI seemed to underestimate and WBGT to overestimate the percentage of thermal

unacceptability. PET showed a poor fit to the data ( $R^2 \approx 0.3$ , Fig. 4); thus, it was excluded from further analyses.

## 4 Discussion

This study examined thermal sensation in the summer conditions of a hot and dry Mediterranean climate and assessed the performance of four thermal indices in terms of their ability to evaluate thermal sensation. Actual thermal sensation differed between some participants' groups: (a) between those in the 18–44-year-old group and those < 18 or > 44 years old, (b) between those visiting the monitoring sites for work and those visiting the sites for rest, entertainment or just passing by, and (c) between those whose health condition on the day of the interview was worse than usual and those who reported they felt as usual or better than usual. Gender, exposure time and history, medical history, perceived risk, familiarity with heat waves, and trust to state institutions were not associated with ATS. The analyses showed that ATS and thermal indices were associated and change in the same direction, i.e., ATS was reportedly in the warm class when thermal indices values were higher. HI, HU, WBGT, and PET showed poor performance based on the applied criteria.

Previous research has shown differences in ATS between men and women. Women are less tolerant to hot thermal conditions than men (Krüger and Rossi 2011; Pantavou et al. 2013b; Cohen et al. 2019) reporting more frequently warm subscales of ATS. An explanation of this finding is the worse thermal insulation of women's clothing (i.e., dresses, skirts) or their psychophysical sensitivity (Parsons 2002). Studies on the effect of age on ATS have produced contradictory results. Some studies suggest that people aged > 55 years show increased sensitivity to thermal conditions (Pantavou et al. 2013b) whereas other studies, including the present one, have found that younger individuals are more sensitive to heat (Krüger and Rossi 2011; Lindner-Cendrowska and Błażejczyk 2018). Moreover, there are studies that found no effect of gender or age on ATS (Bröde et al. 2012). Most participants of the current study reported an uncomfortable thermal state when they felt "slightly warm," "warm," "hot," or "very hot." Compared with the respective findings of similar surveys performed in Athens, Greece (Pantavou et al. 2013b), under a milder climate that placed the comfortable range of thermal sensation between slightly cool to slightly warm, this would indicate some kind of acclimatization of Cypriot respondents, as also discussed in Tochihara et al. (2012) for Japanese and Indonesian people.

The performance of four thermal indices was evaluated in terms of their applicability in the climate of Cyprus. Three indices, HI, HU, and WBGT, are used from weather services to assess hot thermal conditions. The fourth index, PET, is one of the most widely used indices in outdoor thermal perception

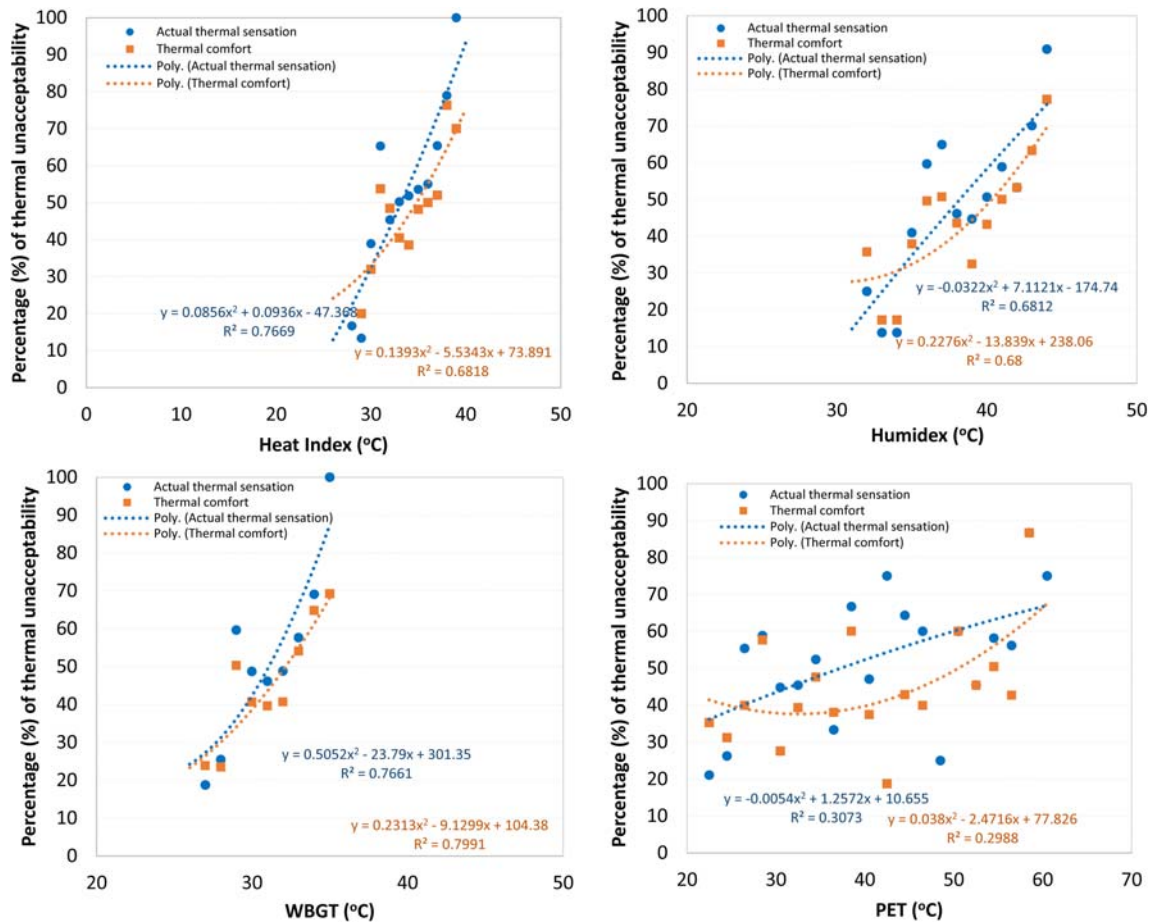


Fig. 4 Percentage of unacceptable thermal sensation based on actual thermal sensation (points + 1 to + 4) and comfort in relation to a Heat Index (HI), b Humidex (HU), c Wet-Bulb Globe Temperature, (WBGT), and d Physiologically Equivalent Temperature (PET)

studies (Potchter et al. 2018). Three statistical and one qualitative criteria were used to evaluate indices’ performance. There were significant differences between thermal indices’ simulations and actual thermal sensation. According to the applied criteria, the performance of the four thermal indices

**Table 7** Thermal indices’ limits of unacceptability in terms of actual thermal sensation (ATS) and thermal comfort (TC)

Thermal index	Limits of unacceptability			
	30%	50%	70%	90%
HI				
ATS	29.5	33.2	36.5	39.5
TC	28.8	34.8	39.0	42.4
HU				
ATS	34.0	38.2	42.6	47.4
TC	33.6	40.3	44.0	47.0
WBGT				
ATS	27.7	31.1	33.3	35.2
TC	28.0	32.1	35.2	37.8

was poor. The indices predicted a narrower range of classes of the thermal assessment scales than the actual thermal sensation and simulated successfully about 12% of the latter. The results improved when simulations were based on modified assessment scales for the Mediterranean climate, as suggested in previous studies (Cohen et al. 2013; Pantavou et al. 2014): the total percentage of correct predictions and the percentage of correct predictions per class of the assessment scale became higher. Nevertheless, a part of the increase in the percentage of correct predictions could be attributed to the collapse of classes + 3 and + 4. PET performed better than HI, HU, and WBGT, based on the original assessment scale, although it showed poor performance in terms of thermal acceptability. Overall, the highest applicability was observed for HImed, i.e., the HI based on the modified Mediterranean climate scale. In a similar study conducted in Athens, Greece (Pantavou et al. 2013a), the same indices scored better predicting on average about 40% of ATS. However, ATS in that study was reported in a 7-point scale and the classes of the indices were adjusted, based on the verbal description of thermal sensation.

The present study has some limitations. Thermal sensation reported by the participants was matched to classes of comfort

(HI), caution categories (HU), and recommended sporting activity (WBGT), which refer to thermal stress. Studies have shown that the concepts of thermal sensation and stress are linked but they are not directly interchangeable (Epstein and Moran 2006). The assessment scale of PET has both a reference to thermal sensation and to the grade of physiological stress. Considering thermal comfort, the scales of thermal sensation and thermal comfort are used by individuals in the same manner (Nicol 2008). In terms of strengths, this is the first study in the local climate of Cyprus. The examined indices can be easily estimated by weather station data. Finally, strengths of this study also include the relatively high number of participants, the use of the 9-point thermal sensation scale that was maintained in the analyses avoiding the merging of different classes of the scales, and the adopted criteria for the indices' assessment that allowed a valid and unambiguous assessment.

There is evidence that the ability of thermal indices to predict thermal sensation differs across climates and that thermal sensation thresholds vary with respect to perceived thermal sensation by individuals in local settings. Therefore, studies on the ability of thermal indices to predict thermal sensation in outdoor environments should be designed and carried out in different climates and countries. Given the potential association between thermal sensation and health, the results of this study can be used from the weather service of Cyprus or other authorities for public health purposes. Moreover, the assessment of thermal conditions of outdoor urban environments can help local authorities and policy makers address economic and social challenges including tourism, planning of cities and urban design, energy conservation, work performance, and productivity.

## 5 Conclusions

HI, HU, WBGT, and PET showed small ability to predict actual thermal sensation in Cyprus. Indices' performance improved when Mediterranean-wise modified climate assessment scales were used. Nevertheless, the predictability of the indices remained low. Overall, HI based on the modified Mediterranean climate showed the highest performance. Similar studies should be conducted to increase knowledge on thermal sensation.

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Giallourous. Investigation: Katerina Pantavou, Niki Michael, Eirini Stylianou, and Rafaella Christou. Data curation: Katerina Pantavou and George Giallourous. Writing—original draft preparation: Katerina Pantavou. Writing—review and editing: Katerina Pantavou, Spyridon Lykoudis, Niki Michael, Eirini Stylianou, Rafaella Christou, Panayiotis Kouis, Filippos Tymvios, Kleantis Nicolaides, Constantinos Cartalis, and Georgios K. Nikolopoulos. Supervision: Katerina Pantavou and Georgios K. Nikolopoulos. Project administration: Katerina Pantavou and Georgios K. Nikolopoulos. Funding acquisition: Georgios K. Nikolopoulos.

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## Compliance with ethical standards

**Conflict of interest** The authors declare that they have no conflict of interest.

**Informed consent** All adults gave verbal informed consent. All minors also gave their assent (verbal) and their parents gave their informed consent (verbal) for their children to participate in the field survey.

## Appendix 1

**Table 8** Assessment scales of Heat Index (HI, °C)

ATS	Heat index (°C)		Category	Possible heat disorders for people in high-risk groups
	Original <sup>a</sup>	Modified (Mediterranean climate) <sup>b</sup>		
+ 1	27–32	< 31.2	Caution	Fatigue possible with prolonged exposure and/or physical activity
+ 2	32–41	31.2–37.2	Extreme caution	Sunstroke, muscle cramps, and/or heat exhaustion possible with prolonged exposure and/or physical activity
+ 3	41–54	> 37.2	Danger	Sunstroke, muscle cramps, and/or heat exhaustion likely. Heatstroke possible with prolonged exposure and/or physical activity
+ 4	≥ 54		Extreme danger	Heat stroke or sunstroke likely

<sup>a</sup> Source: <https://www.weather.gov/safety/heat-index> (accessed 19 Oct 2019)

<sup>b</sup> Source: Pantavou (2014)

**Table 9** Assessment scale of Humidex (HU, °C)

ATS	Humidex (°C)		Degree of comfort
	Original <sup>a</sup>	Modified (Mediterranean climate) <sup>b</sup>	
0			
+1	20–29	< 26.8	Little discomfort
+2	30–39	26.8–35	Some discomfort
+3	40–45	35.1–43.8	Great discomfort; avoid exertion
+4	46 and over	> 43.8	Dangerous; possible heat stroke

<sup>a</sup> Source: <https://www.canada.ca/en/> (Environment and Climate Change—seasonal weather hazards—warm season weather hazards—heat and humidity—guide to summer comfort) (accessed 19 Oct 2019)

<sup>b</sup> Source: Pantavou (2014)

**Table 10** Recommendations for outdoor activity at various Wet-Bulb Globe Temperature (WBGT) ranges

ATS	WBGT (°C)		Recommended sporting activity
	Original <sup>a</sup>	Modified (Mediterranean climate) <sup>b</sup>	
0	< 18	< 23.5	Unlimited
+1	18–23	23.5–28.3	Keep alert for possible increases in the index and for symptoms of heat stress
+2	23–28	28.4–33.7	Active exercise for unacclimatized persons should be curtailed
+3	28–30	> 33.7	Active exercise for all but the well acclimated should be curtailed
+4	> 30		All training should be stopped

<sup>a</sup> Source: <http://www.bom.gov.au/info/wbgt/wbgtrecs.shtml> (accessed 21 Oct 2019)

<sup>b</sup> Source: Pantavou (2014)

**Table 11** Assessment scale of PET

ATS	PET (°C)			Thermal sensation	Grade of physiological stress
	Original <sup>a</sup>	Modified (Mediterranean climate)			
		Athens, Greece <sup>b</sup>	Tel Aviv, Israel <sup>c</sup>		
-4	< 4		<8	Very cold	Extreme cold stress
-3	4–8	≤ 0.7	8–12	Cold	Strong cold stress
-2	8–13	-0.7–5.2	12–15	Cool	Moderate cold stress
-1	13–18	5.2–14.8	15–19	Slightly cool	Slight cold stress
0	18–23	14.8–23.8	19–26	Neutral	No thermal stress
+1	23–29	23.8–31.2	26–28	Slightly warm	Slight heat stress
+2	29–35	31.2–39.1	28–34	Warm	Moderate heat stress
+3	35–41	> 39.1	34–40	Hot	Strong heat stress
+4	> 41		> 40	Very hot	Extreme heat stress

<sup>a</sup> Source: Matzarakis and Mayer (1996)

<sup>b</sup> Source: Pantavou (2014)

<sup>c</sup> Source: Cohen et al. (2013)

## Appendix 2. Equations used for the calculation of thermal indices

- Heat Index (HI, °C)

$$HI = a + b \times T_{air} + c \times RH - d \times T_{air} \times RH - f \times T_{air}^2 - g \times RH^2 + h \times T_{air}^2 \times RH + i \times T_{air} \times RH^2 - j \times T_{air}^2 \times RH^2 \quad (1)$$

where  $a = -8.784695$ ,  $b = 1.61139411$ ,  $c = 2.338549$ ,  $d = 0.14611605$ ,  $f = 1.2308094 \times 10^{-2}$ ,  $g = 1.6424828 \times 10^{-2}$ ,  $h = 2.211732 \times 10^{-3}$ ,  $i = 7.2546 \times 10^{-4}$ , and  $j = 3.582 \times 10^{-6}$

- Humidex (HU, °C)

$$HU = T_{air} + \frac{5}{9}(e - 10) \quad (2)$$

where

$$e = e_s \frac{RH}{100} \quad (B3) \quad \text{and} \quad e_s = 6.112 \times 10^{\frac{7.5 \times T_{air}}{257.7 + T_{air}}} \quad (3)$$

- Wet-Bulb Globe Temperature (WBGT, °C).

$$WBGT = 0.567 \times T_{air} + 0.393 \times e + 3.94 \quad (4)$$

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