

Complying with the demand of standardization in outdoor thermal comfort: a first approach to the Global Outdoor Comfort Index (GOCI)

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ABSTRACT

Over the past ten years the number of studies regarding outdoor thermal comfort has been progressively increasing. However, the existing works are characterized by a certain variety of instruments and methods. An example can be found in the indexes and evaluation scales used to estimate thermal perception. This is why this paper proposes the Global Outdoor Comfort Index (GOCI), which is obtained thanks to the combination of the empirical relations provided by the existing literature. Its independent variables are: air temperature (according to the reported F test value it is the most significant influencing parameter in the new proposed index), mean radiant temperature, relative humidity, wind velocity, latitude, mean annual temperature, mean temperatures of the hottest and coldest months. The index performances were compared to those of the Predicted Mean Vote (PMV), the Physiological Equivalent Temperature (PET), the Mediterranean Outdoor Comfort Index (MOCI) and the Universal Thermal Climate Index (UTCI) by means of an experimental field survey carried out in Rome (Italy). The GOCI reported a total percentage of correct predictions of 27.8%, higher than the PMV (27.7%), PET (25.4%) and UTCI (23.0%) but lower than the MOCI (32.2%). The higher predictive ability of this last index is due to the fact that it was specifically meant for the Mediterranean population. According to Spearman's rho measure of correlation and symmetrical measure of association Gamma calculations, the GOCI was the most sensitive index and it can be used to predict outdoor thermal comfort in areas devoid of studies about specific indexes.

1. Introduction

Currently 54% of the total world population lives in urban areas [1]. Therefore over the past few years an increasing attention has been paid to the planning of thermally comfortable outdoor spaces. Indeed, outdoor thermal comfort is one of the main factors affecting the livability of an area and the number of commercial and recreational activities performed [2] [3]. Moreover comfortable micrometeorological conditions might increase the time people spend outdoors, leading to energy savings due to a reduction in the use of air conditioners [4]. Additionally, the influence of microclimate on human health must be considered too [5]. As a matter of fact some studies [6] [7] [8] [9] [10] [11] revealed an increase in the death rate when air temperature reaches high values. In 2003 a heat wave hit the centre of Europe and Robine et al. [9] [10] reported a total excess mortality of 74,483 deaths considering 16 European countries together. In particular, for those people who are not used to certain heat conditions, there is the risk of

an increase in the death rate even with temperatures which are not considered particularly high. If in the equatorial regions such increase is when air temperature exceeds 32 °C, in cities as London or Stockholm it already occurs at 21–23 °C [8]. These conditions are even intensified due to the complex structure of cities that changes the atmospheric conditions in the urban canopy layer, thus provoking the Urban Heat Island effect, whose intensity varies according to the shape, materials and density of the urban structure.

Moreover, given that future climatic trends point towards the intensification of these effects [12], it is now necessary to develop instruments and methodologies to evaluate outdoor thermal comfort and thermal perception. These instruments must lead to an accurate planning of the urban furniture and materials characterizing the urban texture [13], to the introduction of urban greening [14] [15] [16] and to the development of monitors and alarm systems when the exposed population is at risk [17].

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Nomenclature

ASV	Actual Sensation Vote [-]	MTSV	Mean Thermal Sensation Vote [-]
BF	body fat [kg]	n	minimum size of the sample [-]
C	convective heat flow [W/m ²]	N	population of the city examined [-]
C _p	it measures the difference between the estimated regression model and the real model [-]	OUT_SET*	Outdoor Standard Effective Temperature [°C]
CV	Comfort Value [-]	P	number of explanatory variables put in the regression model [-]
D	diameter of the globethermometer [mm]	PET	Physiological Equivalent Temperature [°C]
E	sampling error [%]	PMV	Predicted Mean Vote [-]
E _D	imperceptible perspiration [W/m ²]	p _{s,sk}	water vapour pressure on the skin [kPa]
E _{Re}	sum of heat flows to heat and humidify the inhaled air [W/m ²]	p _{SET*}	saturated water vapour pressure at SET* [kPa]
E _{Sw}	heat flow related to the evaporation of sweat [W/m ²]	R	net radiation of the body [W/m ²]
ET	Effective Temperature [°C]	R ²	coefficient of determination [-]
FFM	fat-free body mass [kg]	RH	relative humidity [%]
G	global radiation [W/m ²]	S	storage heat flow for heating or cooling the body mass [W/m ²]
GOCI	Global Outdoor Comfort Index [-]	SET*	(rational) Standard Effective Temperature [°C]
h	altitude [m]	sWS	standard deviation of the three measurements performed for the wind velocity during each interview [m/s]
H	height [m]	T _A	air temperature [°C]
h _s	standard heat transfer coefficient [W/m ² °C]	T _{AV}	mean annual temperature [°C]
h _{s,e}	standard evaporative heat transfer coefficient [m ² kPa]	T _{GLOBE}	globe temperature [°C]
H _{SK}	heat loss from the skin [W/m ²]	THI	Temperature-Humidity Index [°C]
I _{CL}	thermal clothing insulation [clo]; it is equal to I _{CL INACTIVE} if M < 1.2 met and to I _{CL ACTIVE} if 1.2 met < M < 2.0 met	T _m	mean temperatures of the coldest month [°C]
I _{CL ACTIVE}	clothing insulation for people who are moving [clo]	T _M	mean temperatures of the hottest month [°C]
I _{CL INACTIVE}	clothing insulation for people who are not moving [clo]	TPV	Thermal Perception Vote [-]
IZA	Thermal comfort Index for cities of Arid Zones [-]	TS	Thermal Sensation [-]
K	Wind Chill Index [W/m ²]	T _{SK}	skin temperature [°C]
L	latitude [°]	TSP	Thermal Sensation Perception [-]
M	metabolic rate [W/m ²]	TSV	Thermal Sensation Vote [-]
M ₁	metabolic rate corresponding to the activity performed during the survey [W/m ²]	UTCI	Universal Thermal Climate Index [°C]
M ₂	metabolic rate corresponding to the activity performed 30 min before the survey [W/m ²]	VIF	Variance Inflationary Factor [-]
M _B	basal metabolic rate [W/m ²]	w	fraction of the wetted skin surface [-]
MOCI	Mediterranean Outdoor Comfort Index [-]	W	weight [kg]
MRT	mean radiant temperature [°C]	W _p	physical work output [W/m ²]
		WS	wind velocity [m/s]
		WS _{MAX}	maximum value measured of the wind velocity [m/s]
		ε	emissivity of the globethermometer [-]

1.1. Outdoor thermal comfort indexes

This is why different indexes and models were developed to predict the perception deriving from the heat exchanges between the human body and the surrounding environment [18] [19]. Many of those were introduced to evaluate the thermal perception in indoor environments [18] [20] and, after some adjustments, they could be used for outdoor environments as well. An example is the Predicted Mean Vote (PMV) [21]: even though its use is suggested by the ISO 7730 [22] and the ASHRAE 55 [23], in order to be adapted to outdoor environments the shortwave radiation had to be included in the model [24]. A similar procedure was required by the (rational) Standard Effective Temperature (SET*) [25], later adapted to the OUT_SET* [26]. For what concerns other indexes, those issues provoked by the prediction of outdoor thermal comfort were due to the assumptions made. That would be the case of the Effective Temperature (ET) [27], which sets the values of the thermal clothing insulation and metabolic rate compatible with a sedentary activity in indoor environments. A similar situation characterizes the Physiological Equivalent Temperature (PET) [28] whose assessment assumes a clothing insulation of 0.9 clo (1 clo = 0.155 m²KW⁻¹) and a metabolic rate of 80 W (which must be added to the basal metabolic rate). On the other hand the reference parameters for the Universal Thermal Climate Index (UTCI) [29] present a walking speed of 1.1 m/s and a metabolic rate of 135 W/m² (hence they refer only to the activity performed).

The difficulties found during the prediction of outdoor thermal comfort also depend on factors as behavioural and social adaptation, physiological adaptation and acclimatization [30]. Hence, in presence of the same microclimatic conditions, a different thermal perception is measured among those living in areas with a different Köppen-Geiger classification [31]. In a study carried out in Europe, Nikolopoulou and Lykoudis [32] examined the thermal comfort in 7 different cities (Athens, Cambridge, Fribourg, Kassel, Milan, Sheffield and Thessaloniki) covering 5 different countries. They reported variations until 10 °C of the neutral temperature and a trend of this variable coinciding with the seasonal climate temperatures. Over the summer, for example, the neutral values of the air temperature are 15.8 °C in Fribourg (Switzerland) and Sheffield (UK), 18.0 °C in Cambridge (UK) and higher than 28 °C in Athens and Thessaloniki (Greece). Rome (Italy) presented a value of 27.2 °C [33], which was slightly lower than the two Greek cities. The situation was similar in winter, with values varying from 10.8 °C in Sheffield (UK) [32] to 22.1 °C in Rome (Italy) [33]. In other studies such difference was stressed through the PET: this is the case of Taichung City (Taiwan) [34], Cairo (Egypt) [35], Hong Kong (China) [36], Sydney (Australia) [26] and Damascus (Syria) [37]. In the last study [37] the differences in terms of thermal perception were also quantified through the OUT_SET × while revealing a certain influence of the alliesthesia [2], a psychological mechanism which let people perceive as comforting any situation that might make feel them warm when microclimatic conditions are cold and vice versa.

Such differences led some studies to focus their attention on the limits of the thermal comfort scales [38] [39] [40] [41] [42] [43]. Md Din et al. [38] adjusted the limits of the categories “partially comfortable” and “uncomfortable” of the Discomfort Index [44] for the Malaysian population. Pantavou et al. [39] calibrated the limits of various index scales in Athens (Greece) and revealed how the probit analysis provided better results than a cubic or linear regression. Kántor et al. [40] stressed different PET thermal sensation ranges between Taiwan and Szeged (Hungary) whereas Lin and Matzarakis [41] performed the same study between Sun Moon Lake (Taiwan) and the Western/Middle Europe. Krüger et al. [42] examined the data obtained through the field surveys in Curitiba (Brazil), Rio de Janeiro (Brazil) and Glasgow (UK) to identify a preliminary procedure for the calibration of the PET. Moreover the PET values corresponding to the different thermal comfort categories were determined and compared. For what concerns the comfort range, a similar comparison was carried out by Hirashima et al. [43]. They stressed the differences characterizing the results of their study in Belo Horizonte and those reported by the studies carried out in other climatic regions.

On the other hand other studies analysed the performances of different indexes, trying to improve their predictive ability. Pantavou et al. [45] discovered how most of the indexes examined were able to predict 35% of the thermal perception votes provided by the interviewees during a field survey in Athens (Greece). Values lower than 25% were revealed by Ruiz and Correa [46] for 6 different indexes in Mendoza (Argentina). Tseliou et al. [47] compared the PET, the Temperature-Humidity Index (THI) [44] and Wind Chill Index (K) [48] showing a strong connection with the local mean climate temperature and they used this variable to adjust the models examined. A similar approach was adopted by Köppe and Jendritzky [49]: though they used a third of the difference between the daily value of the index and its limit. Such procedure allowed the calibration of the limits of the thermal comfort

scale while taking into consideration the acclimatization caused by short times of exposure. On the other hand Chen and Matzarakis [50] modified the PET model developing a new index called modified Physiologically Equivalent Temperature (mPET). It is based on a complex multiple-node body model and it introduces a multiple-layer clothing model able to simulate the water vapour resistance. The mPET also implements an auto changing of clothing insulation whose value ranges between 0.3 and 2.5 clo. Finally Blazejczyk et al. [18] stressed the ability of many indexes to perform a satisfying estimation of the biometeorological variables only in certain microclimatic conditions.

This is why over the past few years an increasing interest in the development of indexes meant for outdoor spaces and able to evaluate the thermal perception of a specific population has been reported. Hence a trend to develop empirical indexes [20] was showed. The methodology which is commonly used requires a field survey where the interviewees are asked to judge the outdoor thermal environment through a subjective judgement scale. At the same time the micro-meteorological variables are measured allowing to obtain, through multiple regressions, models able to predict the human thermal perception. Salata et al. [33] developed the MOCI to evaluate the thermal comfort in the Mediterranean area and in those areas which are part of the Cs category of the Köppen-Geiger climate classification [31]. The performances of this index were then examined by Golasi et al. [51] showing how the MOCI reported a total percentage of correct predictions of 35.5%, leading to better results than indexes as the PMV (32.3%) or the PET (29.6%). Similar empirical indexes were introduced in different countries, thus covering different types of climates and cultures (Fig. 1).

It must be specified though, as showed in Fig. 1, that they are not uniformly distributed on the global territory. Moreover there are different types of independent variables. Some studies used the micro-meteorological variables measured during the field survey [32] [33]

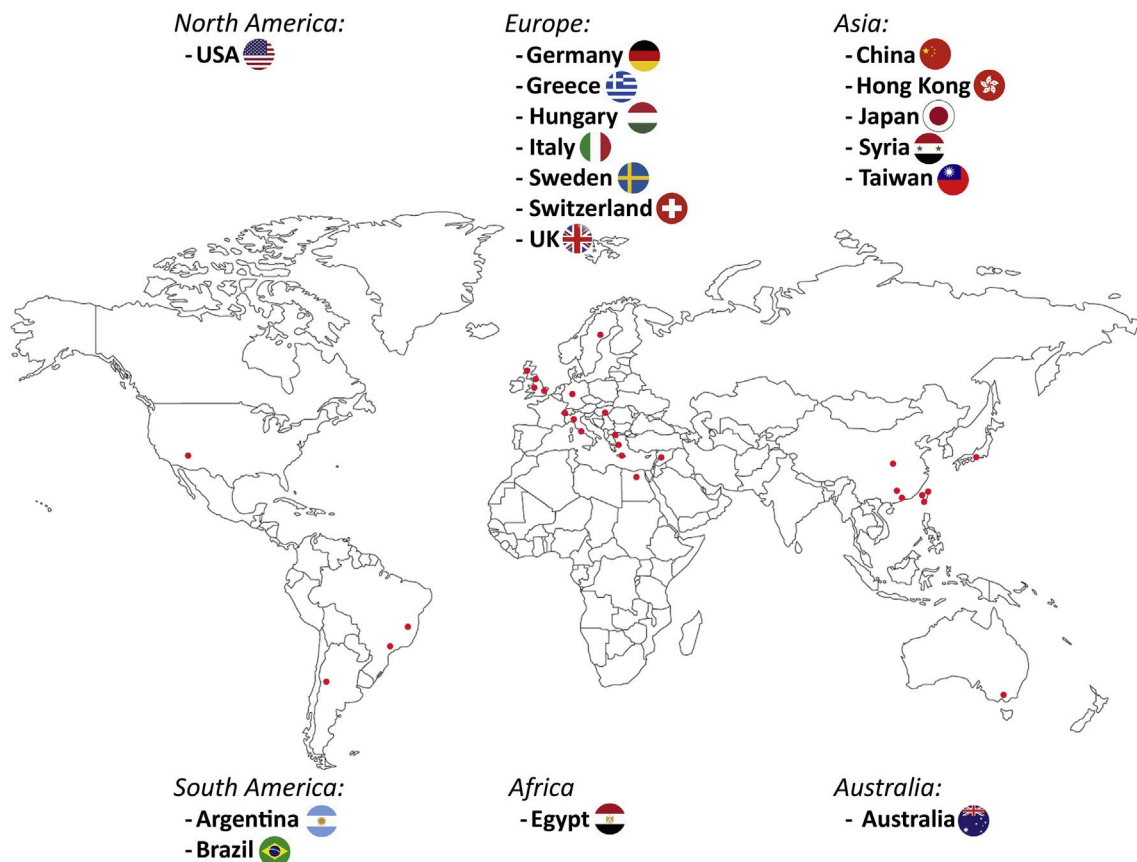


Fig. 1. Identifying the areas where the empirical relations were developed.

[36] [52] [53] [3] [54] [55] [56] and others the corresponding PET [34] [35] [37] [40] [43] [57] [58] [59] [60] [61] [62] [63], SET* [64] or PMV [65] values. Such variety led to some difficulties due to the problem of comparing the results obtained from different studies [20].

1.2. Purpose of the work

For this reason, this study wants to introduce the Global Outdoor Comfort Index (GOCI), an empirical index able to predict the thermal perception in any area or micrometeorological condition. Such index represents the answer to the necessity of a standardization among empirical outdoor thermal comfort indexes [20] and was developed thanks to the combination of different relations that can be found in the existing literature. This new index might represent a useful instrument to plan outdoor spaces in areas or climatic categories where empirical indexes are not developed yet. Hence GOCI performances were compared after a field survey carried out in Rome (Italy) with those of PET, PMV, MOCI and UTCI. The next step was to examine the influence of each variable on the acceptance or rejection of certain microclimatic conditions and the seasonal dependence of the GOCI with respect to the air temperature for the different thermal perception votes classes.

2. Material and methods

2.1. Analytical definition of outdoor thermal comfort indexes

As already specified in the introduction, over the past few years the number of empirical indexes developed through field surveys has been increasing [20]. If in some cases they used as independent variables the measured micrometeorological variables, in other cases they used thermal comfort indexes as the PET [28], SET* [25] and PMV [21]. Therefore this subsection outlines the characteristics of the aforementioned indexes' models. The GOCI is then evaluated through the comparison of its performances with those of PET, PMV, MOCI and UTCI. This is why MOCI and UTCI are part of this subsection as well. Finally the process which led to the development of the GOCI was also described.

The Physiological Equivalent Temperature (PET) [28] is defined as “equivalent to the air temperature that is required to reproduce in a standardized indoor setting and for a standardized person the core and skin temperatures that are observed under the conditions being assessed” [28]. It assumes a thermal clothing insulation of 0.9 clo and a metabolic rate of 80 W (representative value of a light activity) that must be added to the basal metabolic rate. Moreover it considers the mean radiant temperature (MRT) equal to the air temperature T_A , wind velocity WS of 0.1 m/s and sets the water vapour pressure to 12 hPa (a value corresponding to a relative humidity of 50% for $T_A = 20^\circ\text{C}$). It refers to the equation of the thermal balance introduced through the Munich Energy Balance Model for Individual (MEMI) [66] (Eq. (1)):

$$M + W_p + R + C + E_D + E_{Re} + E_{Sw} + S = 0 \quad (1)$$

The PET assessment is then formed by two different steps. The first step is the evaluation of the thermal conditions of the human body through Eq. (1) with a given combination of micrometeorological variables. The second step requires the insertion of the obtained mean skin and core temperatures in the MEMI and wants to solve the equation of the thermal balance for the air temperature T_A (setting, for the other micrometeorological variables, the values previously reported).

The (rational) Standard Effective Temperature (SET*) [25] is defined as “the equivalent temperature of an isothermal environment at 50% RH in which a subject, while wearing clothing standardized for the activity concerned, would have the same heat stress and thermoregulatory strain as in the actual test environment” [25] [67]. The isothermal environment refers to an environment located at the sea level where the mean radiant temperature (MRT) and the air temperature present the same value and the wind velocity is equal to 0. Its

assessment is performed based on Eq. (2) [25] [67]:

$$SET^* = (w_{h,s,e}(p_{s,sk} - 0.5p_{SET^*}) + h_s T_{sk} - H_{sk})/h_s \quad (2)$$

Other studies were carried out referring to the PMV [21]. It is one of the first indexes introduced and it was originally developed for indoor environments through questionnaires submitted to 1,565 interviewees. The original goal was to provide air-conditioning engineers with an instrument that might help them during the realization of comfortable environments. It was adapted to the most complex radiative conditions of the outdoor environment (Eq. (3)) by Jendritzky and Nübler [24] through an approach known as “Klima Michel Model”:

$$PMV = (0.303 \cdot e^{-0.036M} + 0.028) \cdot S \quad (3)$$

where M is the metabolic rate and S refers to the thermal balance of the human body. This index, whose assessment requires 2 operative (metabolic rate M and thermal clothing insulation I_{cl}) and 4 environmental variables (air temperature T_A , mean radiant temperature MRT, relative humidity RH and wind velocity WS), is based on the ASHRAE 7-point scale (cold (-3), cool (-2), slightly cool (-1), neutral (0), slightly warm (+1), warm (+2) and hot (+3)).

The Universal Thermal Climate Index (UTCI) [18] [29] [68] [69] [70] [71] is defined as “an equivalent ambient temperature ($^\circ\text{C}$) of a reference environment providing the same physiological response of a reference person as the actual environment” [18]. It evaluates the physiological response determined by the micrometeorological conditions through a multi-node model of human thermoregulation [72]. Its passive system is characterized by 12 body elements and 187 tissue nodes while the active one analyses the thermoregulatory reactions related to the central nervous system. Its clothing model [73] adjusts the thermal insulation on the different body segments based on the ambient temperature, evaluates the changes in vapour resistance and clothing insulation related to body movement and wind and the wind velocity changes due to a variation of the height above the ground. Moreover, it assumes as reference conditions a walking speed of 1.1 m/s and a metabolic rate of 135 W/m². With respect to the environmental variables, the mean radiant temperature is equal to the ambient temperature and the wind velocity at a height of 10 m is 0.5 m/s. The relative humidity is 50% for temperatures which are lower than or equal to 29 $^\circ\text{C}$ and 20 hPa for higher temperatures.

The Mediterranean Outdoor Comfort Index (MOCI) [33] [74] is the result of a study performed in Rome, hence it is specific for those subjects who are used to the Mediterranean climate. The analytic expression is (Eq. (4)):

$$MOCI = -4.068 - 0.272 \cdot WS + 0.005 \cdot RH + 0.083 \cdot MRT + 0.058 \cdot T_A + 0.264 \cdot I_{CL} \quad (4)$$

As the PMV, it is able to predict the thermal perception through the ASHRAE 7-point scale.

This scale is also the most used among those studies which led, through different field surveys, to the development of the empirical relations combined to obtain the Global Outdoor Comfort Index (GOCI) (Table 1).

While examining the relations seeing among the independent variables the micrometeorological ones, it is possible to notice how the air temperature, the wind velocity and the relative humidity are the most common. Among the relations provided referring to the PET it is interesting to notice how they are all linear except for that suggested by Kantor et al. [40] [57] in Szeged (Hungary). Then two equations, one for Chiayi, Taichung and Yunlin (Taiwan) and the other for Crete (Greece), are reported in function of SET* and PMV respectively.

For what concerns the city of Rome, the relation listed in Table 1 for the Mediterranean Outdoor Comfort Index was developed for this specific study. This new relation was obtained by exploiting the experimental data which led to the original index equation [33] and doesn't see the thermal clothing insulation as explanatory variable.

Table 1
Empirical indexes and studies developed through field surveys.

City	Votes	Equation	Scale
Mendoza, Argentina [53]	622	IZA = 0.9796 + 0.0621 T _A -0.3257 WS+0.0079 RH	(-2)-(+2)
Sao Paulo, Brazil [56]	1,750	TSP = -3.557 + 0.0632 T _A +0.0677 MRT+0.0105 RH-0.304 WS	(-3)-(+3)
Guangzhou, China [52]	1,582	ASV* = -8.527 + 0.245 T _A -0.457 WS+0.059 MRT+0.013 RH	(-3)-(+3)
Hong Kong [36]	286 ^a	TS = -4.77 + 0.1185 T _A -0.6019 WS+0.0025 SR+0.1155 RH	(-3)-(+3)
Wuhan, China [55]	490	TSV _{WUHAN} = -1.382 + 0.0643 T _A +0.00076 G-0.161 WS-0.00376 RH	(-1)-(+1)
Kassel, Germany [32]	824	ASV = -0.876 + 0.043 T _A +0.0005 G-0.077 WS+0.001 RH	(-2)-(+2)
Athens, Greece [32]	1,503	ASV = -0.412 + 0.034 T _A +0.0001 G-0.086 WS-0.001 RH	(-2)-(+2)
Thessaloniki, Greece [32]	1,813	ASV = -2.197 + 0.036 T _A +0.0013 G-0.038 WS+0.011 RH	(-2)-(+2)
Milan, Italy [32]	1,173	ASV = -0.92 + 0.049 T _A -0.0002 G+0.006 WS+0.002 RH	(-2)-(+2)
Rome, Italy [33] ^b	941	MOCI = -3.649-0.273 WS+0.005 RH+0.086 MRT+0.044 T _A	(-3)-(+3)
Yokohama, Japan [3]	1,134 ^c	TS = 1.2 + 0.1115 T _A +0.0019 SR-0.3185 WS	(+1)-(+7)
Fribourg, Switzerland [32]	1,920	ASV = -0.69 + 0.068 T _A +0.0006 G-0.107 WS-0.002 RH	(-2)-(+2)
Birmingham, UK [54]	451	CV = 3.2464 + 0.0665 T _A -0.2256 WS-0.0079 RH+0.0011 SR	(+1)-(+5)
Cambridge, UK [32]	948	ASV = -1.74 + 0.113 T _A +0.0001 G-0.05 WS-0.003 RH	(-2)-(+2)
Sheffield, UK [32]	1,008	ASV = -0.855 + 0.07 T _A +0.0012 G-0.057 WS-0.003 RH	(-2)-(+2)
Melbourne, Australia [59]	1,059	Women: MTSV = 0.162 PET-3.4355Men: MTSV = 0.144 PET-2.9399	(-3)-(+3)
Belo Horizonte, Brazil [43]	1,693	Hot season: MTSV = -8.12 + 2.94 log (PET) Cool season: MTSV = -5.34 + 1.61 log (PET)	(-3)-(+3)
Guangzhou, China [62]	1,005	Winter: TSV = -2.81 + 0.18 PET Spring: TSV = -6.40 + 0.25 PET Summer: TSV = -0.36 + 0.07 PET	(-4)-(+4)
Cairo, Egypt [35]	300	Hot season: MTSV = 0.145 PET-3.625 Cold season: MTSV = 0.071 PET-2.479	(-3)-(+3)
Cairo, Egypt [60]	320	Summer: MTSV = 0.0998 PET-2.947 Winter: MTSV = 0.0881 PET-2.1411	(-3)-(+3)
Szeged, Hungary [40] [57]	967	TSV = -0.004 PET ² +0.278 PET-3.61	(-4)-(+4)
Umeå, Sweden [63]	525	MTSV = -1.81 + 0.1365 PET	(-3)-(+3)
Damascus, Syria [37]	920	Summer: TSV = 0.060 PET-0.941 Winter: TSV = 0.114 PET-2.755	(-4)-(+4)
Taichung, Taiwan [34]	505	Hot season: MTSV = 0.118 PET-3.025 Cool season: MTSV = 0.199 PET-4.722	(-3)-(+3)
Glasgow, UK [61]	573	TS = 0.118 PET-1.5919	(-3)-(+3)
Tempe, USA [58]	1,284	MTSV = 0.08 PET-2.4	(-4)-(+4)
Chiayi, Taiwan [64]	1,644 ^d	Hot season: MTSV = 0.130 SET*-3.814	(-3)-(+3)
Taichung, Taiwan [64]	1,644 ^d	Cool season: MTSV = 0.074 SET*-2.066	(-3)-(+3)
Yunlin, Taiwan [64]	1,644 ^d		
Crete, Greece [65]	800	ASV = 0.16 PMV+0.22	(-2)-(+2)

^a Group of 8 students.

^b Relation determined for this case study.

^c Group of 6 students.

^d Total for the 3 cities.

Among the relations listed in Table 1, the only equation able to evaluate changes in the thermal clothing insulation is the one carried out in Crete (Greece) (the independent variable is the PMV). This is why the first step during the development of the GOCI was to define a series of variables that had to be set as independent. They were: air temperature T_A, mean radiant temperature MRT, relative humidity RH, wind velocity WS and, with respect to the examined location, latitude L, altitude h, mean annual temperature T_{AV}, mean temperatures of the hottest T_M and coldest T_m months (Table 2). These two last variables take into consideration the annual temperature swing [42].

Those variables concerning the geographical location of the site are important to evaluate the influence of factors as adaptation, acclimatization and thermal expectation whereas the micrometeorological variables outline the specific environmental configuration to examine.

Table 1 reports some studies where the solar radiation was considered among the independent variables. On the other hand in this study the mean radiant temperature was inserted in the explanatory variables of the GOCI: if it is true that a variation in the solar radiation can lead to a variation in the mean radiant temperature, it cannot be stated the same in the opposite situation. Hence an empirical relation able to connect both variables was obtained while using the experimental data sampled in urban environments during the field surveys carried out from February 2014 to January 2015 by Salata et al. in [33] and from June 2015 to April 2016 by Golasi et al. in [51] and in the present study. In this equation the solar radiation and the mean radiant temperature are the dependent and independent variable respectively. This allowed to substitute in Table 1 the solar radiation with a relation

based on the mean radiant temperature. A similar approach was adopted with the PET, SET* and PMV. In this case the sampled experimental data of air temperature, wind velocity, relative humidity and mean radiant temperature were used as input values in the Rayman software [76] which gave as output the corresponding values of the 3 aforementioned thermal comfort indexes. Then Eqs. (5)–(7) (Table 3) where the PET, SET* and PMV were the dependent variables were obtained and this allowed to write all the equations listed in Table 1 based on the 4 micrometeorological variables previously selected for the GOCI.

The next step was to evaluate the results provided by the empirical relations listed in Table 1. Therefore the values of air temperature, wind velocity, relative humidity and mean radiant temperature sampled in [33], in [51] and in the present study were inserted in each equation. However some studies reported in Table 1 differ in the used thermal perception scale. This is why the results were adjusted according to the ASHRAE 7-point scale (the same assumed for the GOCI) and it was then possible to set them as dependent variables. On the other hand the explanatory variables were determined assigning to each one of the aforementioned results the corresponding values of the micrometeorological variables, latitude, altitude, mean annual temperature, mean temperatures of the hottest and coldest months. The values of the last five variables (reported in Table 2) change according to the cities where the relations of Table 1 were developed.

It was then possible to make an evaluation of the multicollinearity through the VIF (Variance Inflationary Factor) analysis among the 9 variables previously selected. The collinear variables do not add any

Table 2
Climatic features of the cities where the empirical relations were obtained and investigated seasons.

City	Investigated period	L	T _{AV} [75]	T _M [75]	T _m [75]	h
Mendoza, Argentina [53]	July, December	32.4° S	16.4 °C	24.0 °C	8.1 °C	824 m
Sao Paulo, Brazil [56]	Summer, winter	23.3° S	18.5 °C	21.5 °C	15.4 °C	760 m
Guangzhou, China [52] [62]	All year ^a	23.1° N	22.2 °C	28.8 °C	13.9 °C	21 m
Hong Kong [36]	Summer, winter	22.3° N	22.6 °C	28.4 °C	15.4 °C	3 m
Wuhan, China [55]	August to November	30.4° N	17.2 °C	29.4 °C	4.0 °C	37 m
Kassel, Germany [32]	All year	51.3° N	9.1 °C	17.7 °C	0.2 °C	133–615 m
Athens, Greece [32]	All year	38.0° N	18.1 °C	27.9 °C	9.5 °C	70–338 m
Thessaloniki, Greece [32]	All year	40.6° N	15.9 °C	26.5 °C	5.2 °C	0–250 m
Milan, Italy [32]	All year	45.5° N	13.1 °C	23.8 °C	1.9 °C	122 m
Rome, Italy [33]	All year	41.5° N	15.7 °C	24.4 °C	7.7 °C	21 m
Yokohama, Japan [3]	All seasons	35.4° N	9.1 °C	21.9 °C	−2.6 °C	24 m
Fribourg, Switzerland [32]	All year	46.8° N	8.1 °C	17.0 °C	−0.9 °C	643 m
Birmingham, UK [54]	August–February	52.5° N	9.2 °C	15.7 °C	3.2 °C	140 m
Cambridge, UK [32]	All year	52.2° N	9.7 °C	16.6 °C	3.1 °C	6 m
Sheffield, UK [32]	All year	53.4° N	9.6 °C	16.2 °C	3.8 °C	75 m
Melbourne, Australia [59]	November–May	37.5° S	14.8 °C	20.3 °C	9.4 °C	31 m
Belo Horizonte, Brazil [43]	March, July	19.5° S	25.0 °C	26.3 °C	23.2 °C	858 m
Cairo, Egypt [35]	Summer, winter	31.0° N	21.3 °C	27.6 °C	13.1 °C	23 m
Cairo, Egypt [60]	June, July, December	31.0° N	21.3 °C	27.6 °C	13.1 °C	23 m
Szeged, Hungary [40] [57]	Autumn, spring	46.3° N	10.8 °C	20.8 °C	−1.4 °C	75 m
Umeå, Sweden [63]	July, August	63.5° N	2.7 °C	15.9 °C	−9.7 °C	12 m
Damascus, Syria [37]	Summer, winter	33.6° N	16.9 °C	26.2 °C	6.9 °C	700 m
Taichung, Taiwan [34]	All year	24.1° N	22.1 °C	27.6 °C	15.7 °C	91 m
Glasgow, UK [61]	March to July	55.9° N	8.5 °C	14.5 °C	3.0 °C	40 m
Tempe, USA [58]	All year	33.4° N	21.5 °C	32.7 °C	11.4 °C	360 m
Chiayi, Taiwan [64]	Winter to summer	23.3° N	23.2 °C	27.9 °C	17.4 °C	69 m
Taichung, Taiwan [64]	Winter to summer	24.1° N	22.1 °C	27.6 °C	15.7 °C	91 m
Yunlin, Taiwan [64]	Winter to summer	23.7° N	18.8 °C	26.4 °C	10.6 °C	53 m
Crete, Greece [65]	February, July	35.3° N	19.0 °C	26.5 °C	12.2 °C	0–184 m

^a It takes into consideration the investigated period in the two different studies.

relevant value to the model and, as Marquardt [77] states, those variables characterized by VIF values higher than 10 should be excluded. Therefore in this study the altitude, which highly depends on the corresponding temperature values, is eliminated. Then, in order to identify the most fitting model, the 8 remaining variables were combined through a Best Subsets analysis. It gave the possibility to compare 254 possible models based on the adjusted R^2 and the C_p statistic. The first criterion is important because it allows to evaluate models with a different number of independent variables, whereas the other refers to the difference between the estimated regression model and the real model. The C_p statistic leads to examine only those models characterized by a value of this parameter lower than or equal to $p + 1$, where p is the number of explanatory variables considered. In this study the model with the best values of these parameters sees the simultaneous use of the 8 variables and led to the relation of the Global Outdoor Comfort Index (GOCI) (Eq. (8)):

$$GOCI = -0.908 + 0.053 \cdot MRT + 0.084 \cdot T_A + 0.006 \cdot RH - 0.229 \cdot WS - 0.056 \cdot T_{AV} - 0.026 \cdot T_M - 0.042 \cdot T_m + 0.009 \cdot L \quad (8)$$

In this case the C_p statistic is 8, the adjusted R^2 0.379 and the Pearson coefficient 0.616.

2.2. Field survey

To compare the performances of the GOCI with those of PET, PMV, MOCI and UTCI, the field survey originally carried out to estimate the MOCI performances [51] was extended to winter and spring as well.

Therefore the investigation began in June 2015 and ended in April 2016. This allowed the evaluation of a wide range of climatic conditions (Table 4).

The sample of the interviewees is of 869 subjects. This value satisfied the requirements since it exceeded the 400 units of the minimum sample [42] determined through Eq. (9):

$$n = \frac{N \cdot (1/E^2)}{N + (1/E^2)} \quad (9)$$

where n is the minimum size of the sample, N the population of the examined city and E is the sampling error (assumed to be 5%).

Every subject was asked to fill a questionnaire complying with the ISO 10551 [78] (Fig. 2).

The first part asked about personal questions as age, gender, weight, height, how long they lived in that city, clothing, activity performed both during the interview and 30 min before the interview, time of exposure. The second part asked the interviewee to judge the thermo-hygrometric perception through the ASHRAE 7-point scale. It must be specified though that people who took part in the survey were chosen randomly and, according to Krüger et al. [61], only during the post-processing phase it was possible to exclude people who lived less than 6 months in that city and pregnant women. Moreover the only analysed data were those provided by the subjects who, at the moment of the questionnaire, were exposed to the outdoor conditions for at least 15 min. With reference to the indoor thermal comfort this is the minimum space residency suggested by the ASHRAE Standard 55 [23] to take into consideration those factors affected by the thermal

Table 3
Relations between the indexes PET, PMV and SET* and the micrometeorological variables mean radiant temperature, air temperature, relative humidity and wind velocity.

PET = $-3.157 + 0.424 \cdot MRT + 0.684 \cdot T_A + 0.014 \cdot RH - 2.272 \cdot WS$	$R^2 = 0.99$	Eq. 5
PMV = $-5.257 + 0.099 \cdot MRT + 0.104 \cdot T_A + 0.012 \cdot RH - 0.634 \cdot WS$	$R^2 = 0.81$	Eq. 6
SET* = $+4.288 + 0.478 \cdot MRT + 0.199 \cdot T_A + 0.021 \cdot RH - 3.236 \cdot WS$	$R^2 = 0.83$	Eq. 7

Table 4
Micrometeorological background of the experimental measurements and the corresponding interviews.

	MRT [°C]	T _A [°C]	RH [%]	WS [m/s]	PET [°C]
Minimum	9,98	10,47	25,50	0,02	8,40
Maximum	48,07	35,86	92,10	2,50	42,80
Mean	24,13	21,45	56,40	0,66	21,06
Mode	19,62	11,87	56,00	0,80	30,00
Median	24,11	22,21	56,00	0,54	21,30
Std. Deviation	7,70	5,80	13,72	0,45	6,85
25 th percentile	18,29	15,59	46,20	0,33	15,30
75 th percentile	29,56	25,82	65,00	0,87	25,80
Skewness	0,37	0,05	0,27	1,10	0,24
Kurtosis	−0,24	−1,01	−0,21	0,93	−0,54

adaptation. Such assumption can be confirmed through the study carried out by Yang et al. [79] in Singapore. Even though the Kruskal-Wallis H test showed that the mean thermal sensation vote was not statistically different for those experiencing a different time of

exposure, it was possible to notice how a longer exposure to outdoor conditions helped the human body to adapt better, becoming more tolerant to thermal stresses.

During each interview the air temperature, the globe temperature, the wind velocity, relative humidity and global radiation were measured. A pyranometer was used to measure the global radiation, whereas the other variables were measured through 4 probes connected to a mobile microclimate control unit (Fig. 3).

Table 5 reports the metrological properties of the used instruments.

The instruments were placed at a distance that was lower than 3 m with respect to the interviewee [2] and the height was regulated according to the centre of gravity in the human body [80]. Therefore the height was set to 0.6 m for those sitting and 1.1 m for those standing.

All the interviewees needed about 90 s to fill the questionnaire. Consequently three measurements were performed for each variable while relating to the thermal perception of each interviewee the corresponding mean value. Moreover, everytime that the measurement location was modified, a time equal to the response time of the sensors was allowed before measuring new values and submitting the

OUTDOOR THERMAL COMFORT QUESTIONNAIRE

This questionnaire is entirely voluntary. If you do not wish to complete it, or any part of it, you are under no obligation to do so.

Fig. 2. The summer questionnaire used in this study (the list of clothing ensembles is adjusted based on the surveyed period of the year).

Date: / /		Time: :		Questionnaire n°:	
1	Gender:				
	<input type="checkbox"/> Male <input type="checkbox"/> Female				
2	Age:				
				
3	Weight:				
 kg				
4	Height:				
 m				
5	Time of residency:				
	<input type="checkbox"/> less than 6 months <input type="checkbox"/> more than 6 months				
6	Time spent outdoors:				
 minutes				
	For the last half hour have you been mainly:				
7	<input type="checkbox"/> sleeping <input type="checkbox"/> sitting <input type="checkbox"/> standing <input type="checkbox"/> walking <input type="checkbox"/> doing sports <input type="checkbox"/> other (please specify):				
	Your current activity is:				
8	<input type="checkbox"/> sitting <input type="checkbox"/> standing <input type="checkbox"/> walking <input type="checkbox"/> doing sports <input type="checkbox"/> other (please specify):				
	What are you wearing right now?				
9	<input type="checkbox"/> trousers, short-sleeve shirt <input type="checkbox"/> trousers, long-sleeve shirt <input type="checkbox"/> trousers, long-sleeve shirt, suit jacket <input type="checkbox"/> trousers, long-sleeve shirt, suit jacket, vest, T-shirt <input type="checkbox"/> trousers, long-sleeve shirt, long-sleeve sweater, T-shirt <input type="checkbox"/> knee-length skirt, short-sleeve shirt (sandals) <input type="checkbox"/> knee-length skirt, long-sleeve shirt, full slip <input type="checkbox"/> knee-length skirt, long-sleeve shirt, half slip, long-sleeve sweater <input type="checkbox"/> knee-length skirt, long-sleeve shirt, half slip, suit jacket <input type="checkbox"/> ankle-length skirt, long-sleeve shirt, suit jacket <input type="checkbox"/> walking shorts, short-sleeve shirt <input type="checkbox"/> sweat pants, long-sleeve sweatshirt Add/remove garments:				
10	How do you feel at this precise moment?				
	<input type="checkbox"/> cold <input type="checkbox"/> cool <input type="checkbox"/> slightly cool <input type="checkbox"/> neutral <input type="checkbox"/> slightly warm <input type="checkbox"/> warm <input type="checkbox"/> hot				

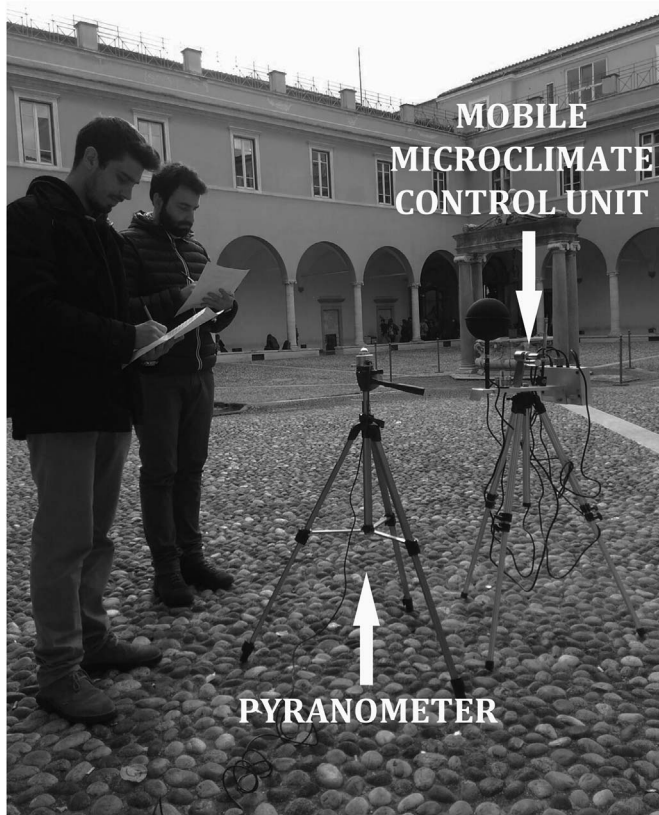


Fig. 3. Used instruments during the field survey.

questionnaires to the interviewees. This procedure allowed to take into account the instrument thermal inertia.

It was then necessary to determine the value of the mean radiant temperature MRT which in climates characterized by low wind velocity values, as in Rome, is the variable affecting the most the outdoor thermal comfort [33]. This is why Eq. (10) was used [80]:

$$T_{MR} = \left[(T_{GLOBE} + 273.15)^4 + \frac{1.1 \cdot 10^8 \cdot WS^{0.6}}{\varepsilon \cdot D^{0.4}} \cdot (T_{GLOBE} - T_A) \right]^{0.25} - 273.15 \quad (10)$$

where ε and D are the emissivity (0.97) and the diameter (150 mm) of the globethermometer.

On the other hand the evaluation of the wind velocity requires a different approach and even its variability must be computed. For this reason Eq. (11) was used, introduced by Oliveira and Andrade [81] and Andrade et al. [82]:

$$WS = WS_{MAX} + sWS \quad (11)$$

where WS_{MAX} is the maximum value measured and sWS is the standard deviation of the three measurements performed. The wind direction was not considered because walking is the most performed activity by the interviewees in those areas where the field survey took place and

their walking direction continuously changes due to the urban morphology (classified into the Local Climate Zone 2₃ [83]).

For each questionnaire the corresponding values of the operative variables were also evaluated. In particular, the metabolic rate M was assessed as an average value among those corresponding to the activities performed both during the survey (M_1) and 30 min before (M_2) (Eq. (12)) [23] [84]:

$$M = 0.7 \cdot M_1 + 0.3 \cdot M_2 \quad (12)$$

Once M was determined, it must be added to the basal metabolic rate M_B , assessed in function of the fat-free body mass FFM (Eq. (13)) [85]:

$$M_B = 0.0484 \cdot (19.7 \cdot FFM + 743) \quad (13)$$

where the fat-free body mass FFM was obtained by subtracting the body fat BF from the body weight. The body fat BF can be calculated both for men and women through Eqs. (14) and (15), respectively [86]:

$$BF = 0.685 \cdot W - 5.86 \cdot H^3 + 0.42 \quad (14)$$

$$BF = 0.737 \cdot W - 5.15 \cdot H^3 + 0.37 \quad (15)$$

However the PET and PMV, indexes that were compared to the GOCI, were calculated through the Rayman software [76], which requires the metabolic rate in Watt. Therefore the result provided by the sum of M and M_B was multiplied by the skin surface of each interviewee that was previously assessed thanks to the W (weight) and H (height) values reported in the questionnaire through Eq. (16) [23]:

$$\text{Dubois area} = 0.202 \cdot (W^{0.425} \cdot H^{0.725}) \quad (16)$$

For what concerns the assessment of the thermal clothing resistance, the subjects were provided with a list of different clothing ensembles [23]. This enabled the evaluation of the thermal clothing insulation $I_{CL \text{ INACTIVE}}$. However it is important to remember that when the body moves the air goes through the clothes openings and/or some air movements occur underneath them. Hence, if the activity performed presents a metabolic rate higher than 1.2 met (1 met = 58.2 W/m²), the corresponding thermal clothing insulation $I_{CL \text{ ACTIVE}}$ is determined through Eq. (17):

$$I_{CL \text{ ACTIVE}} = I_{CL \text{ INACTIVE}} \cdot (0.6 + 0.4/M) \quad (17)$$

The underwear garments were also computed [52]. Thus to the thermal clothing insulation previously determined the value of 0.03 clo and 0.04 clo for men and women respectively was added. Moreover an increase in the clothing insulation for those sitting with clothing ensembles characterized by a standing insulation values between 0.5 clo and 1.2 clo [23] was taken into account. To be more specific, the increase was of 0.01 clo if the subject was sitting on a wooden stool (a chair located in the porticos of the university campus). The PET values were determined with a thermal clothing insulation of 0.9 clo according to its original model [28] even if Chen and Matzarakis [50] have recently introduced the modified Physiologically Equivalent Temperature (mPET), a new index based on a multiple-layer clothing model and an auto changing of clothing insulation.

Table 5

Metrological properties of the instruments used to measure the micrometeorological variables.

Type of probe	Measured variable	Measured range	Resolution	Accuracy
PT 100 platinum resistance thermometer	T_A [°C]	(-50)–(+80)	0.01	± 0.5 °C above -7 °C
Hot-wire anemometer	WS [ms ⁻¹]	(0)–(45)	0.01	± 1 m/s
Forced ventilation psychrometer	RH [%]	(0)–(100)	0.1	± 3% (0–90%), ± 4% (90–100%)
Globethermometer	T_{GLOBE} [°C]	(-40)–(+80)	0.01	≤ 0.1 °C at 0 °C DIN 43760 1/3
Pyranometer	G [Wm ⁻²]	(0)–(2000)	10 ⁻³	± 5%

3. Results and discussions

3.1. Examining the GOCI relation and the influence of independent variables

For the development of the Global Outdoor Comfort Index (GOCI), the empirical relations reported in different studies carried out in various parts of the world (Table 1) were combined.

It is interesting to notice how, if the values of latitude, mean annual temperature, mean temperature of the hottest and coldest months related to the city of Rome were included in Eq. (8), the result would be an intercept of -2.372. With respect to a given city, the intercept value represents the perception that would be reported if the values of the other variables were equal to zero and, in this case, it is about 1.3 units higher than the one provided by the MOCI. As a matter of fact it is important to consider that the MOCI is an index calibrated to evaluate the thermohygrometric perception of the Mediterranean population. On the other hand the GOCI also includes relations representative of cities with cold climates whose populations are used to thermal stresses caused by low temperatures and this leads to the intercept variation towards values characterizing an hotter thermal perception. The opposite situation occurs if the city examined is Sheffield (UK). Table 1 reports that the Actual Sensation Vote determined by zero set for all the variables would be -0.855. Differently with the climatic parameters of the city the intercept of the GOCI would be -1.546, with a consequent variation corresponding to a colder sensation. Contrary to what happened in Rome (Italy), in Sheffield (UK) the variation was provoked by the fact that the GOCI computed the contributions of cities and areas characterized by a hot climate as Sao Paulo (Brazil), Crete (Greece), Tempe (USA) and so on.

It is also interesting to examine some aspects concerning the mean annual temperature and the mean temperatures of the hottest and coldest months. These variables are related to factors as thermal expectation and acclimatization and it can be noticed, through the coefficients reported in the GOCI relation (Eq. (8)), how if these variables increase the thermal perception reports lower and higher thermal stresses during hot and cold periods respectively. This is testified by the fact that high mean temperatures reveals a mild climate leading people to be tolerant to certain microclimatic conditions. The opposite situation occurs with the latitude characterized by a positive coefficient in Eq. (8).

Then it should be specified that a linear model was chosen due to the unstructured trend of the residuals and the presence of a significant relation between the independent variables and the GOCI is revealed through the F test value (1,583). Indeed it is higher than 1.94, which is the 95th percentile of the Fischer's pdf for a distribution F with 8 and 22,584 degrees of freedom (representatives of the number of independent variables and occurrences respectively). It is also important to evaluate the existence of a significant linear relation between the variables and the GOCI. This relation occurs if the values assumed for the t statistic exceed the range ± 1.960 , determined through the percentile values for the distribution t of Student with 22,584 degrees of freedom and a significance level of 0.05. In particular this occurs for the air temperature (24.70), the mean radiant temperature (22.11) and wind velocity (-10.83) and inevitably affects the influence of each variable on the model. Fig. 4 reports the values of the partial F test which are normalized with respect to the maximum value determined. That happened with the air temperature and this is why in Fig. 4 this variable reports the value of 1.00.

It is possible to notice how the mean radiant temperature and wind velocity also provide a relevant contribution on the GOCI. However the high influence of the air temperature is due to the fact that, in order to develop the model of the new index, relations obtained in windy climates were also implemented. In such cases the air temperature becomes the most influential variable since it bestrides the convective heat exchange [17] [28]. This is the opposite situation if compared to

climates that are not windy, where the mean radiant temperature is the one affecting the most the outdoor thermal comfort [87]. An example can be found in the city of Rome [33].

Fig. 5 confirms the high influence of the air temperature and mean radiant temperature on the thermal perception. It reports the normalized partial F test values with respect to the maximum obtained value in function of latitude and mean annual temperature for the 4 environmental variables included in the GOCI relation. The values have been obtained by analysing the relations listed in Table 1. Therefore, the graph of each variable was developed based on as many points as the aforementioned relations. Once a locality is chosen, it is possible to access in the graph thanks to the latitude and mean annual temperature values. Thus, the influence of the variable on the thermal perception of that specific population can be estimated. The interpolation was performed through the method “kriging” (also known as technique of Wiener–Kolmogorov prediction). It is common in geostatistics and gives the possibility to minimize the mean square error [88].

It can be noticed (Fig. 5) how the influence of the air temperature decreases in those areas near the equator where the values of global radiation have a higher influence. In the same areas a certain influence of the relative humidity was reported. Probably it is a consequence of its combination with high values of air temperature. For what concerns the wind velocity it is important to notice that the higher values of the partial F test are revealed when mean annual temperatures are low for most of the latitudes.

3.2. Comparing the GOCI with other indexes

The GOCI was compared to other commonly used biometeorological indexes, as the PMV, PET, MOCI and UTCI. The PET and PMV are respectively the first and second most used index to evaluate outdoor thermal comfort [20], the MOCI was specifically developed to analyze the thermal perception in the Mediterranean area [33] and the UTCI was conceived to cover the whole climate range from heat to cold [73]. The comparison, performed after a field survey carried out in the city of Rome (Italy), was based on 3 statistical criteria and a qualitative one [39] [45]. The first is the Spearman's rho measure of correlation, which is a nonparametric statistical measurement of correlation between the values predicted by the indexes and those provided by the interviewees. The second is the symmetrical measure of association Gamma and, while examining the variables at an ordinary level, it investigates the relation connecting the classes predicted by the indexes and the votes of the interviewees.

The third criterion examines the total percentage of correct predictions. For example while analysing the PMV and a vote provided by an interviewee of -2, the prediction can be considered correct if the corresponding index value (assessed through the values of the operative variables provided by the questionnaires and the measured environmental variables) ranges between -2.5 and -1.5. The last criterion, the qualitative one, evaluates the percentage of correct predictions with

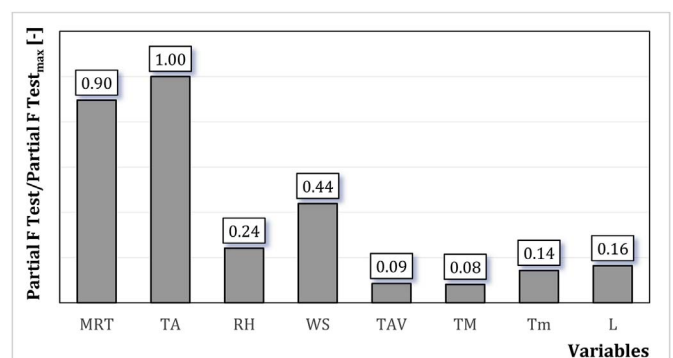


Fig. 4. Normalized partial F test values with respect to the maximum value obtained.

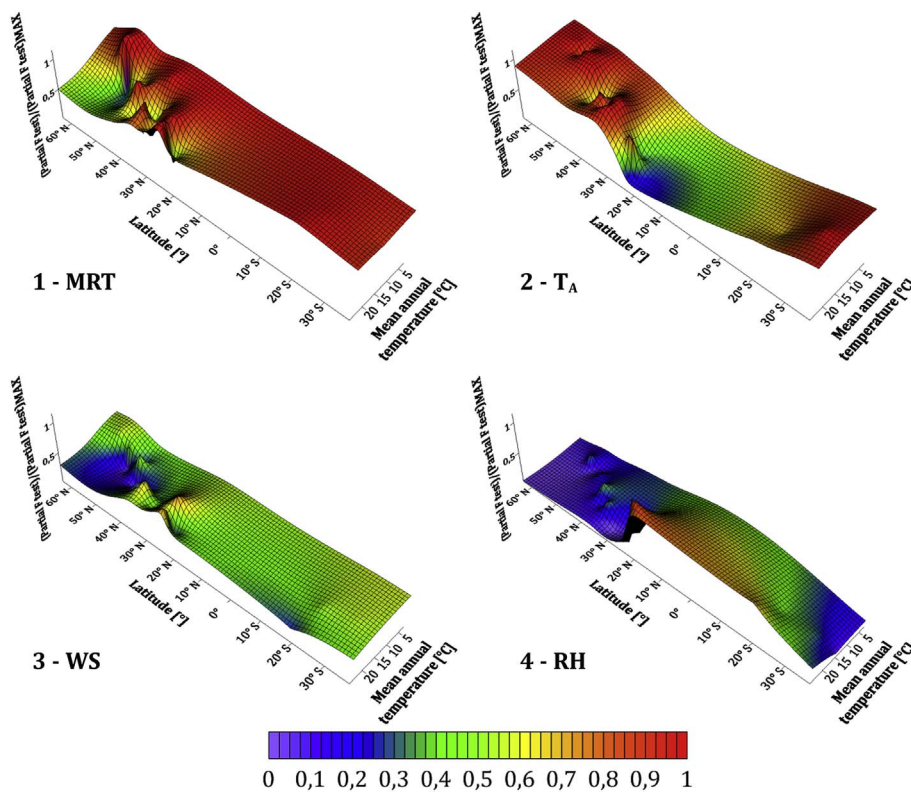


Fig. 5. Partial F test values normalized with respect to the maximum obtained value in function of latitude and mean annual temperature for the mean radiant temperature MRT (1), air temperature T_A (2), wind speed WS (3) and relative humidity RH (4).

respect to the classes of the indexes (Table 6) through a cross-tabulation analysis.

Table 7 shows the obtained results with respect to the 3 statistical criteria.

While observing the reported values (Table 7) it is possible to notice how the MOCI is the best predictive index for the thermal perception. It reports a total percentage of correct predictions of 32.2%, the highest value for the Spearman's rho measure of correlation and the third best result for the symmetrical measure of association Gamma. For what concerns the GOCI performances, it is the most sensitive index, as showed through the high values of the correlation coefficients. In particular, the Gamma coefficient experiences an improvement of 0.06 units with respect to the MOCI. The GOCI also reports a total percentage of correct predictions of 27.8%, which is 4.4% lower than the MOCI though it is higher than the PMV, PET and UTCI (respectively 0.1%, 2.4% and 4.8%). With regard to the PET it should be said that an improvement in the performances could be obtained if the modified Physiologically Equivalent Temperature (mPET) [50] is taken into consideration. As a matter of fact the mPET implements a multiple-layer clothing model and adjusts the clothing insulation based on the outdoor conditions. It should also be said that the value obtained through the MOCI was due to the fact that the field survey was carried out in Rome and the index was developed according to the thermal

Table 7

Total percentage of correct predictions and correlation coefficients between the values predicted by the indexes and those provided by the interviewees.

Index	Coefficients		Percentage of the correct predictions [%]
	Spearman [-]	Gamma [-]	
GOCI	0.551	0.630	27.8
MOCI	0.555	0.568	32.2
PET	0.547	0.562	25.4
PMV	0.522	0.526	27.7
UTCI	0.482	0.652	23.0

sensations of people living in the Cs category of the Köppen-Geiger climatic classification (which characterizes the Mediterranean area). Such index is also able to consider some elements related to adaptation as the thermal clothing insulation (variable that people change to modify their own thermal perception) [51]. Therefore in Rome, where the field survey was carried out, the MOCI performances represent a sort of limit for the GOCI. Even if its performances can't reach those provided by the MOCI, it is possible to lessen such discrepancy by improving its model through the addition of relations representing different areas.

Table 6

Thermal perception and corresponding indexes categories.

Thermal perception [-]	GOCI [-]	MOCI [-]	PET [°C] ^a	PMV [-]	UTCI [°C]	Classes of the indexes
-3	< -2.5	< -2.5	< 4	< -2.5	< -27	-3
-2	-2.5 ÷ -1.5	-2.5 ÷ -1.5	4 ÷ 8	-2.5 ÷ -1.5	-27 ÷ -13	-2
-1	-1.5 ÷ -0.5	-1.5 ÷ -0.5	8 ÷ 18	-1.5 ÷ -0.5	-13 ÷ 9	-1
0	-0.5 ÷ +0.5	-0.5 ÷ +0.5	18 ÷ 23	-0.5 ÷ +0.5	9 ÷ 26	0
+1	+0.5 ÷ +1.5	+0.5 ÷ +1.5	23 ÷ 35	+0.5 ÷ +1.5	26 ÷ 38	+1
+2	+1.5 ÷ +2.5	+1.5 ÷ +2.5	35 ÷ 41	+1.5 ÷ +2.5	38 ÷ 46	+2
+3	> +2.5	> +2.5	> 41	> +2.5	> 46	+3

^a Scale suggested by Matzarakis and Mayer [89].

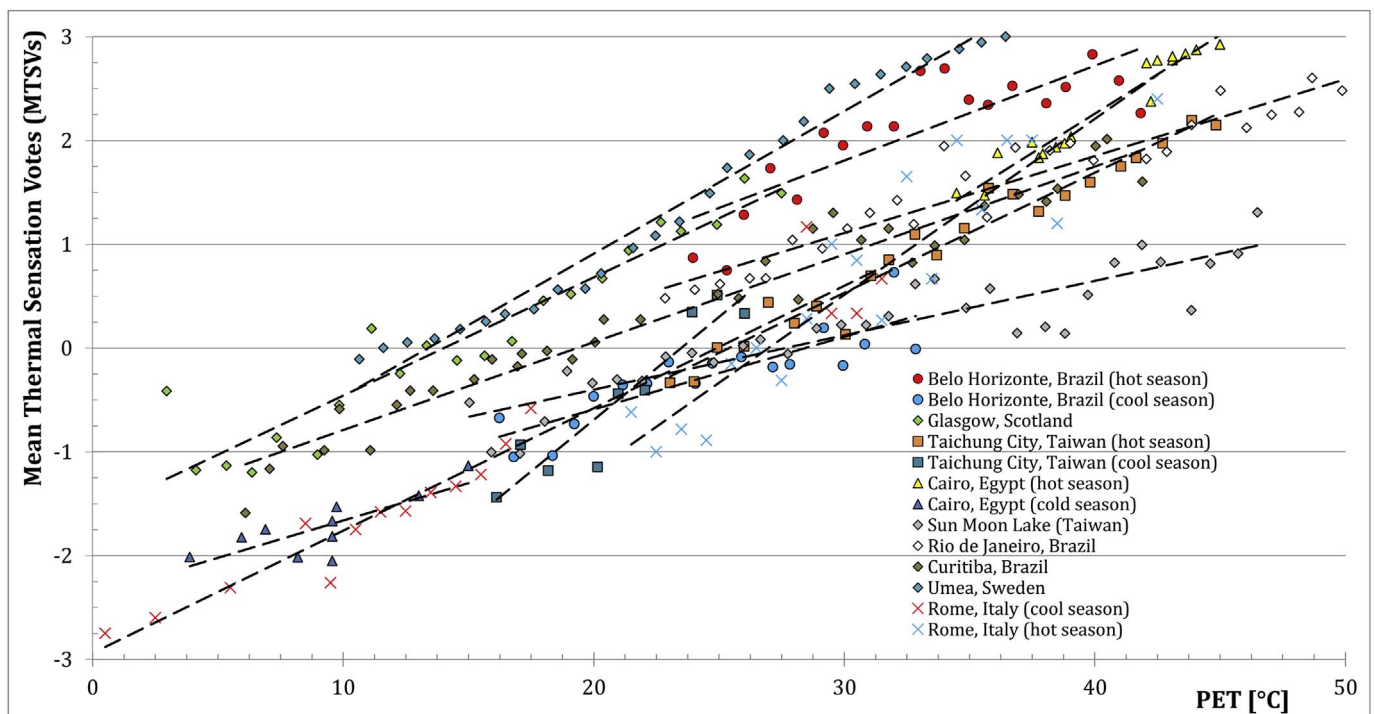


Fig. 6. Binned mean thermal sensation votes with respect to the PET in those cities where the empirical relations were developed through the ASHRAE 7-point scale: Belo Horizonte, Brazil [43], Glasgow, Scotland [61], Taichung City, Taiwan [34], Cairo, Egypt [35], Sun Moon Lake, Taiwan [41], Rio de Janeiro, Brazil [42], Curitiba, Brazil [42], Umea, Sweden [63], Rome, Italy [33].

As the MOCI represents a limit for the performances of the GOCI in Rome, the same situation occurs in all those cities where a specific empirical relation was developed (Table 1). This is due to the fact that the GOCI combines the results of different researches (Table 1). Fig. 6 reports, while considering the PET, the mean thermal sensation votes of those studies that used the ASHRAE 7-point scale.

Therefore during the outdoor thermal comfort prediction the GOCI takes into consideration the low mean thermal sensation votes revealed during the cold season in Cairo (Egypt) and, at the same time, the higher values of those registered (thermal stress being the same) in Glasgow (Scotland) or Umeå (Sweden).

However one of the advantages is that it was developed through relations meant for outdoor environments. Hence the values of the correlation coefficients and the total percentage of correct predictions are higher than those of the PET or PMV (although the PMV considers operative variables such as the metabolic rate and thermal clothing insulation). Therefore the GOCI can be considered a reliable and useful instrument for the analysis of the outdoor thermal comfort in all those places lacking of an empirical index.

The considerations made are confirmed when, through a cross-tabulation analysis [39] [45], the percentage of correct predictions for each class of the indexes is examined (Fig. 7). In this case, given the class of an index (Table 6), the sum of the percentages of the various thermal perception votes is 100%. While taking as an example the GOCI, 290 interviewees were required to evaluate the thermal environment in micrometeorological conditions corresponding to the class 0 of the index. Among these interviewees, 29 chose the vote -3, 108 the vote -2, 67 the vote -1, 74 the vote 0 and 12 the vote +1. This led to graph the percentages of 10.0%, 37.2%, 23.1%, 25.5% and 4.2% respectively. Moreover the ideal situation is when 100% is registered in correspondence to the “identity line”: this means that the predictions are all correct. Therefore the value 100% should be reported in the intersection between the class of the index -3 and the thermal perception vote -3, between the class of the index -2 and the thermal perception vote -2 and so on. If high percentage values are located on the right side of the “identity line” the index will overestimate the thermal

perception; on the other hand if high values are located on the left side the index will underestimate it.

As showed in Fig. 7, it is possible to notice how the MOCI is the index presenting the highest performances: indeed it is characterized by values higher than 25% on the whole “identity line”. Good results were also obtained by the GOCI and PMV, with values slightly lower than 40% for the classes +2 and +3. Then the lower level of predictive ability of the PET is confirmed and the value of 80% in correspondence of the class +3 and the thermal perception vote +3 should not mislead (it is influenced by the low number of occurrences (5)). On the other hand the low total percentage of correct predictions of the UTCI is mainly due to the high number of interviewees who chose the votes 0 and -1 to judge the thermal environment with micrometeorological conditions related to the categories of the index -1 and 0 respectively.

It should be also noticed how in Fig. 7 the classes characterizing the GOCI go from 0 to +3. As previously said, this is due to the insertion in the model of this index of empirical relations determined through field surveys performed in cold climates. Indeed Fig. 8 shows that, with thermal stress being the same, the GOCI is about 1.4 units higher than the corresponding value of the MOCI. This leads to a higher thermal tolerance with respect to low temperatures and low PET values and, at the same time, to an increase in the predicted thermal stress in hot conditions.

According with Tseliou et al. [47], the influence of the air temperature and the season on the relation between the votes provided by the interviewees and the values predicted by the GOCI was also examined. An outdoor thermal comfort index should be characterized by a certain predictive stability in every climatic context. For example, if a subject judges the thermal environment with a thermal perception vote of -1, the corresponding GOCI value should range between -1.5 and -0.5. According to Table 6, there should be a coherence between the different thermal perception votes and the corresponding GOCI intervals. However, Fig. 9 shows how this happens mainly for the thermal perception vote 0 in the cold season and for the thermal perception vote +1 in the hot season.

In the other cases a certain influence of air temperature, thermal

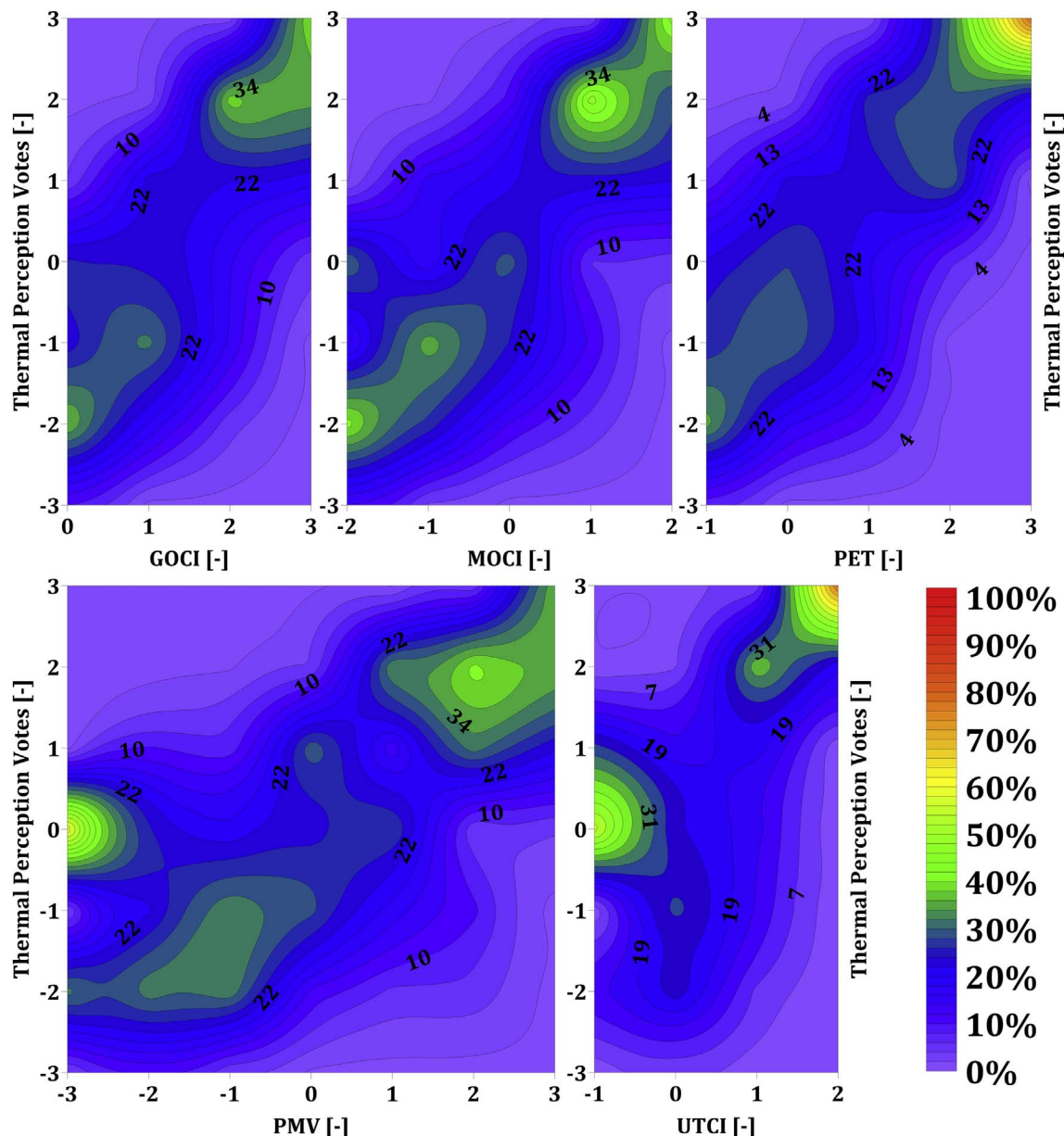


Fig. 7. Percentage of correct predictions with respect to the classes of the GOCI, MOCI, PET, PMV and UTCI.

adaptation and acclimatization phenomena was reported. This partially confirms the results obtained by Tseliou et al. [47] for the PET, Temperature-Humidity Index (THI) and Wind Chill Index (K). Moreover it is interesting to notice how for the thermal perception votes -1, 0 and +1 the slope of the regression line for the cold season is slightly higher than the one characterizing the summer, stressing a higher sensitiveness in the subjects. Finally the thermal perception votes (+2) and (+3) were not discussed because there were not enough occurrences for the cold season. The same situation concerned the thermal perception vote (-3) for the hot season.

4. Conclusions

This study tried to develop an empirical index able to fulfil the demand of standardization whose relevance has been stressed more than once by the researchers working in this field.

For this reason all the empirical relations, determined through field surveys in outdoor environments, were previously identified in the existing literature. However they differ for the micrometeorological

variables inserted in the suggested models, the used scales and the cities where the studies were carried out. Therefore it was necessary to adjust the results of all the relations (obtained thanks to micrometeorological data sampled over different field surveys) according to the ASHRAE 7-point scale and at the same time explain them through the same variables (air temperature, mean radiant temperature, wind velocity and relative humidity). The results provided by the empirical relations were then set as dependent variables, whereas the aforementioned 4 micrometeorological variables and, with respect to the location, latitude, mean annual temperature, mean temperatures of the hottest and coldest months and altitude as independent variables. The statistical analysis that followed gave the possibility to:

- exclude the altitude through the evaluation of the multicollinearity and Variance Inflationary Factor (VIF);
- combine the remaining variables through a Best Subsets analysis in 254 possible models to identify the most performing one and determine the relation of the Global Outdoor Comfort Index (GOCI). Its explanatory variables are air temperature, mean radiant

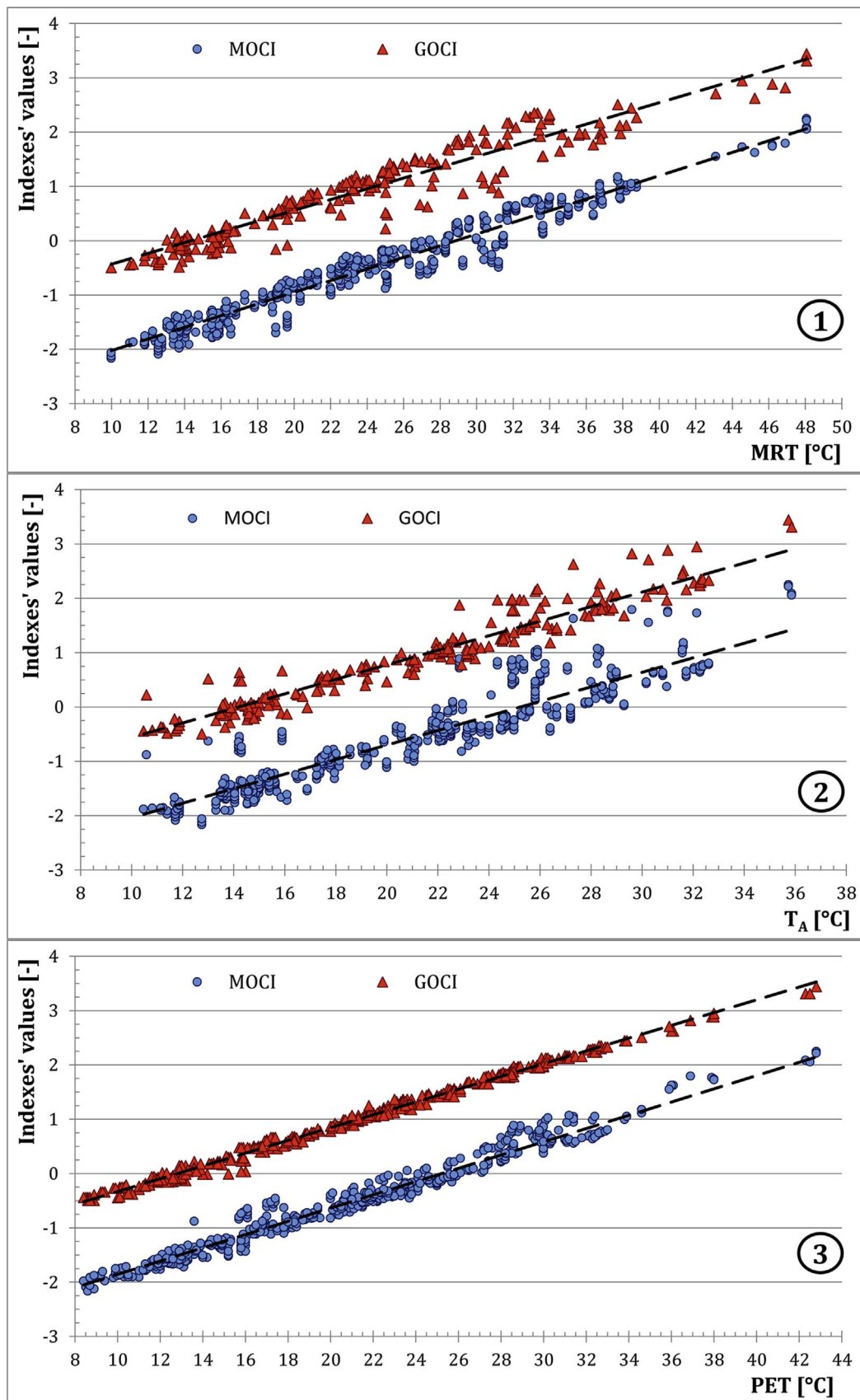


Fig. 8. Values of the MOCI and GOCI with respect to the mean radiant temperature (1), air temperature (2) and PET (3).

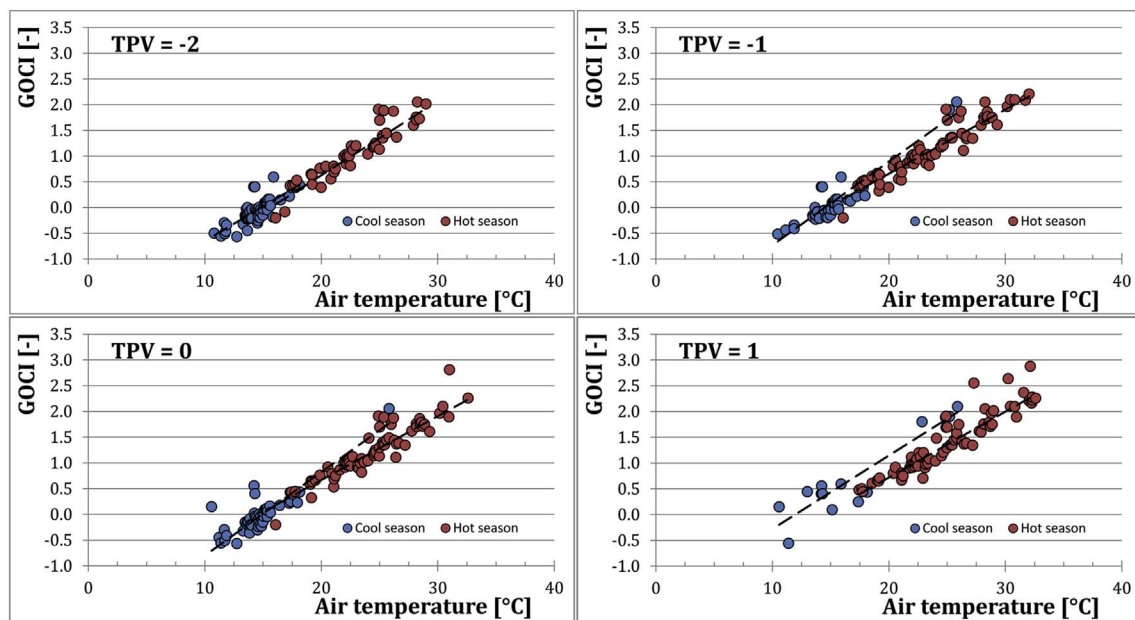


Fig. 9. Seasonal dependence of the GOCI with respect to the air temperature for the classes of the thermal perception votes -2, -1, 0 and + 1.

temperature, relative humidity, wind velocity, latitude, mean annual temperature, mean temperatures of the hottest and coldest months. The model chosen for the GOCI also reported a value of the C_p statistic of 8, an adjusted R^2 of 0.379 and a Pearson coefficient of 0.616;

- notice how the ability of the GOCI to identify the peculiarity of a specific city lies in the simultaneous use, in the model, of the micrometeorological variables together with other variables such as latitude, mean annual temperature, mean temperatures of the hottest and coldest months;
- reveal how the air temperature is the most influencing variable in the GOCI, followed by the mean radiant temperature and wind velocity.

The performances of the new developed index were then compared to those of the PET, PMV, MOCI and UTCI. To perform such comparison a field survey in Rome (Italy) was necessary: it was performed in areas presenting different characteristics in terms of microclimate, topography and urban morphology from June 2015 to April 2016, thus covering all seasons. The transversal analysis concerned a statistical sample of 869 subjects using structured questionnaires filled simultaneously to the measurement of the air temperature, globe temperature, wind velocity, relative humidity and global radiation. The comparison allowed to state that:

- the GOCI reported a total percentage of correct predictions of 27.8% and is the most sensitive index. Indeed the Spearman's rho measure of correlation and the symmetrical measure of association Gamma are 0.551 and 0.630 respectively;
- with a total percentage of correct predictions of 32.2% the most performing index was the MOCI. However, while examining the results, it is important not to forget the peculiarity, in terms of acclimatization, adaptation and thermal expectations related to each population. The field survey used for the evaluation of the indexes performances was carried out in Rome (Italy) and this is why the MOCI, calibrated to study the thermal perception of the Mediterranean population, was the most performing one. The GOCI was developed taking into account models based on the thermal perception of different populations and it will not be as fitting as an empirical index in the city or in the area where it was developed. However it might achieve such relevance by implementing in the

model relations characterized by a certain uniformity in terms of thermal perception scale, independent variables and adopted methodology (instruments used and metrological properties, the method used to determine the mean radiant temperature and wind velocity, the number of interviewees, types of demographic and personal information collected);

- the GOCI can be considered a valid instrument for the analysis of the outdoor thermal comfort and perception in all those areas devoid of specific empirical indexes for the local population.

However examining the performances of the GOCI through a field survey carried out in one city only (i.e., Rome) can be a limit to the validation process. For what concerns future developments, it is important to examine the performances of the GOCI even in other nations or climate categories. Moreover it must be specified that it will be necessary to update constantly the index inserting in the model the empirical relations which will be developed. A further interesting study can be the comparison of its predictive ability with the one of recent indexes as the modified Physiologically Equivalent Temperature.

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