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ORIGINAL PAPER

Development of outdoor thermal index indicating universal and separate effects on human thermal comfort

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Abstract The purpose of this study is to propose a new outdoor thermal index that simultaneously indicates universal and separate effects. The value indicating universal effect in this index consists of the summation of air temperature and the effective temperature differences by air velocity, longwave radiation, solar radiation, and humidity. This paper describes the theoretical construction of this newly derived index to compare with previous indices. The calculations of the new index are demonstrated using the observed data in order to explicitly indicate the specific features of the new index.

Keywords Outdoors · Human heat equilibrium · Solar radiation · Universal effect · Separate effect

Introduction

The number of empirical and theoretical studies on indoor thermal comfort contrasts sharply with the relative paucity of those for outdoors, as is commonly known. Beside the four reasons suggested by Spagnolo and de Dear (2003), this paucity appears to be due to the fact that there are few useful indices that consider solar radiation, in addition to air temperature, longwave radiation, humidity, wind velocity, metabolic rate, and garment insulation. Although several indices based on heat balance between the human body and the outdoor environment, such as the modified ET* for outdoors (Umemura and Horikoshi 1991), physiological equivalent temperature (Hoeppe 1999; Matzarakis et al. 1999), and the OUT_SET* (Pickup and de Dear 2000) are already available, and the International Society of Biometeorology (ISB) has made exhaustive and sophisticated efforts to form a commission to develop a universal thermal climate index UTCI (ISB 2009), all these evaluate only overall thermal effect. This study proposes a new thermal index for outdoors which indicates separate effects of environmental variables, as well as overall effect. It is to be expected that this index will inform to what extent universal feeling depends on each environmental variable and will indicate which elements need to be adjusted for universal thermal comfort. Here is the different and advanced feature compared with previous indices.

The main purpose of this study is to derive, mathematically, the theory of how universal and separate effects in the outdoor thermal environment are simultaneously indicated, not to test whether this new index is more accurate in representing universal feeling than previous indices. Secondly, this paper discusses how this newly derived index is superior to the other existing indices—modified ET*, OUT_SET*, and UTCI—through the calculated results.

Mathematical construction of the effective temperature ET*

The modified ET* (Umemura and Horikoshi 1991), OUT_SET* (Pickup and de Dear 2000), and the new index in this study have all been derived to develop the effective temperature ET* by Gagge et al. (1971, 1986), on the basis of the heat balance equation between the human body and

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the outdoor thermal environment. Prior to the derivation of the new index, this section runs through the mathematical construction of the ET*.

According to Newton's law of cooling, the convective heat loss from the outer surface of a clothed body C (W/m^2) is expressed as follows:

$$C = h_c f_{cl}(t_{cl} - t_a) \tag{1}$$

where h_c [W/(m^{2}K)], f_{cl} (n.d.), t_{cl} (°C), and t_a (°C) are convective heat transfer coefficient, clothing area factor, mean temperature of the outer surface of the clothed body, and air temperature, respectively.

The net heat loss of radiation from the outer surface of the clothed body R (W/m^2) can be expressed as follows:

$$R = h_r f_{cl}(t_{cl} - t_r) \tag{2}$$

where h_r [W/(m^{2}K)] and t_r (°C) are radiant heat transfer coefficient and mean radiant temperature, respectively. The coefficient h_r can be expressed as follows:

$$h_r = e\sigma f_{rd}\left(T_{cl}^4 - T_r^4\right)(T_{cl} - T_r) \tag{3}$$

where ε (n.d.), σ [W/(m^{2}K^4)], f_{rd} (n.d.), T_{cl} (K), and T_r (K) are average emissivity of the clothed body, Stefan-Boltzmann constant, effective radiation area factor, mean temperature of the outer surface of the clothed body in Kelvin and mean radiant temperature in Kelvin, respectively.

Winslow et al. (1937) developed an operative temperature OT (°C).

$$\begin{aligned} C + R &= h_c f_{cl}(t_{cl} - t_a) + h_r f_{cl}(t_{cl} - t_r) \\ &= h f_{cl}(t_{cl} - \mathrm{OT}) \end{aligned} \tag{4}$$

$$\mathrm{OT} = (h_c t_a + h_r t_r)/h \tag{5}$$

where h [W/(m^{2}K)] is a combined heat transfer coefficient.

$$h = h_c + h_r \tag{6}$$

Dry heat loss from skin through clothing is equal to the sum of the convective and radiative heat loss at the outer surface of the clothed body.

$$C + R = (t_{sk} - t_{cl})/0.155 I_{cl} \tag{7}$$

where I_{cl} (clo) is clothing insulation. Eq. (4) and Eq. (7) can be combined to eliminate t_{cl}:

$$C + R = h F_{cl} f_{cl}(t_{sk} - \mathrm{OT}) \tag{8}$$

where F_{cl} (n.d.) is the thermal efficiency factor of clothing.

$$F_{cl} = 1/(1 + 0.155 h f_{cl} I_{cl}) \tag{9}$$

Therefore, Eq. (1) and Eq. (2) are rewritten as follows:

$$C = h_c F_{cle}(t_{sk} - t_a) \tag{10}$$

$$R = h_r F_{cle}(t_{sk} - t_r) \tag{11}$$

$$F_{cle} = F_{cl} f_{cl} \tag{12}$$

Thus, Eq. (10) and Eq. (11) indicate the convective and radiative heat loss from skin, respectively. F_{cle} (n.d.) is effective clothing thermal efficiency.

The evaporative heat loss from the skin surface E (W/m^2) can be expressed as follows:

$$E = w h_e'\left(p_{sk,s} - p_a\right) \tag{13}$$

where w (n.d.), $p_{sk,\ s}$ (kPa), and p_a (kPa) are skin wettedness, saturated water vapor pressure at t_{sk}, and water vapor pressure at t_a, respectively. The evaporative heat transfer coefficient including the actual clothing effect h'_e [W/(m^{2}kPa)] is expressed using evaporative heat transfer coefficient h_e [W/(m^{2}K)], permeation efficiency factor of clothing F_{pcl} (n.d.), and effective surface area of clothing f_{cl} (n.d.).

$$h_e' = h_e F_{pcl} f_{cl} = h' i_m \mathrm{LR} \tag{14}$$

As presented above, h'_e is also expressed using overall dry heat transfer coefficient including the actual clothing effect h' [W/(m^{2}K)], total vapor permeation efficiency i_m (kPa/K), and Lewis ratio LR (K/kPa). The coefficient h' can be expressed as follows:

$$h' = h F_{cle} \tag{15}$$

From the dry heat loss of Eq. (8) and the evaporative heat loss of Eq. (13), the total heat loss from the skin surface Q_{sk} (W/m^2) can be expressed as follows:

$$Q_{sk} = C + R + E = h'(t_{sk} - \mathrm{OT}) + w h_e'\left(p_{sk,s} - p_a\right) \tag{16}$$

Fobelets and Gagge (1988) shifted the balance between the operative temperature and humidity without altering the total heat loss from skin.

$$\begin{aligned} Q_{sk} &= h'\left[\left(t_{sk} + \frac{wh_e'}{h'} p_{sk,s}\right) - \left(\mathrm{OT} + \frac{wh_e'}{h'} p_a\right)\right] \\ &= h'\left[\left(t_{sk} + \frac{wh_e'}{h'} p_{sk,s}\right) - \left(\mathrm{HOT} + \frac{wh_e'}{h'} p_{\mathrm{HOT},s}\right)\right] \\ &= h'\left[\left(t_{sk} + \frac{wh_e'}{h'} p_{sk,s}\right) - \left(\mathrm{ET^*} + 0.5\frac{wh_e'}{h'} p_{\mathrm{ET^*},s}\right)\right] \end{aligned} \tag{17}$$

where HOT (°C), $p_{\mathrm{HOT},\ s}$ (kPa), ET* (°C), and $p_{\mathrm{ET^*},\ s}$ (kPa) are the humid operative temperature (Nishi and Gagge 1971), saturated water vapor pressure at HOT, the effective temperature (Gagge et al. 1971, 1986), and saturated water vapor pressure at ET*, respectively. HOT is the hypothetical air temperature of an isothermal environment at 100% relative humidity that yields the same skin wettedness and total heat loss from the skin as for the actual environment.

$$\mathrm{HOT} = \mathrm{OT} + \frac{wh_e'}{h'}\left(p_a - p_{\mathrm{HOT},s}\right) \tag{18}$$

Gagge et al. (1971, 1986) converted HOT into ET* by the change of reference humidity. ET* is the temperature of a hypothetical isothermal environment at 50% relative humidity that yields the same skin wettedness and total heat loss from the skin as for the actual environment.

$$\mathrm{ET}^* = \mathrm{OT} + \frac{wh_e'}{h'}\left(p_a - .05p_{\mathrm{ET}^*,s}\right) \tag{19}$$

The velocity, activity, and clothing insulation in the hypothetical environment are all the same as in the actual environment, in the case of ET*. A standard effective temperature SET* is defined to refer another standard environment (Gagge et al. 1986). The clothing insulation in this standard environment I_{cls} is:

$$I_{cls} = 1.3264/(\mathrm{M} - \mathrm{W} + 0.7383) - 0.0953 \tag{20}$$

The standard convective heat transfer coefficients is defined by:

$$h_{cs} = 5.66(\mathrm{M} - 0.85)^{0.39} \tag{21}$$

where h_{cs} is never lower than 3.0 (W/m^{2}K), corresponding to $8.6v^{0.53}$ at the air velocity v=0.137 (m/s).

That is, SET* is the temperature of a hypothetical isothermal environment at 50% relative humidity in which a person, wearing clothing standardized for the activity concerned, has the same skin wettedness and mean skin temperature as in the actual environment (ASHRAE 2009). This standardization is designed so that SET* remains 24°C at PMV=0.

Derivation of new index

The index ETV proposed by Horikoshi et al. (1995), which can indicate universal effect and separate effects of environmental variables simultaneously, is defined as the ET* to refer another standard environment differing from those in the cases of ET* and SET*. The velocity and clothing insulation in this standard environment are 0.1 m/s and 0 clo, respectively. Assuming that the convective heat loss at this standard environment corresponds to the heat loss C of Eq. (10) while t_a equals to a hypothetical air temperature t_v (°C), the loss C can be expressed as follows:

$$C = h_{co}F_{cleo}(t_{sk} - t_v) \tag{22}$$

where h_{co} [W/(m^{2}K)] and F_{cleo} (n.d.) are convective heat transfer coefficient in the standard environment and effective clothing thermal efficiency in the standard environment, respectively. The following equation is derived from Eq. (10) and Eq. (22).

$$C = h_{co}F_{cleo}(t_{sk} - t_v) = h_cF_{cle}(t_{sk} - t_a) \tag{23}$$

Horikoshi et al. (1991) defined the temperature t_v in this equation as the wind velocity temperature, which indicated the air temperature including the cooling effect of air movement. The temperature t_v is expressed from Eq. (23) as:

$$t_v = t_a + \frac{\mathrm{TVF}}{h_{co}F_{cleo}} \tag{24}$$

$$\mathrm{TVF} = h_{co}F_{cleo}(t_v - t_a) = (h_{co}F_{cleo} - h_cF_{cle}) \times (t_{sk} - t_a) \tag{25}$$

TVF (W/m^2) indicates the effective temperature difference in air temperature caused by the cooling power of air movement and is defined as the net convective energy exchanged on the exposed body surface. This quantity is referred to as the thermal velocity field (Horikoshi et al. 1991).

Gagge et al. (1967) developed an effective radiant field ERF (W/m^2) from the definition of the operative temperature described in Eq. (8), to separate the effect of thermal radiation. It is noted that the radiative heat loss R in Eq. (8) and this ERF consist of longwave component of radiation, therefore R_L (W/m^2) as the heat loss of longwave radiation and ERFL (W/m^2) as an effective longwave radiant field are used in the following equations.

$$C + R_L = h'(t_{sk} - \mathrm{OT}) \tag{26}$$

$$\mathrm{OT} = t_a + \frac{\mathrm{ERFL}}{h'} \tag{27}$$

$$\mathrm{ERFL} = h_rF_{cle}(t_r - t_a) \tag{28}$$

The heat loss by convection and longwave radiation $C+R_L$ described in Eq. (26) can be rewritten by Eq. (11) and Eq. (22).

$$\begin{aligned} C + R_L &= h_{co}F_{cleo}(t_{sk} - t_v) + h_rF_{cle}(t_{sk} - t_r) \\ &= h_v(t_{sk} - \mathrm{OTV}) \end{aligned} \tag{29}$$

where h_v [W/(m^{2}K)] is overall heat transfer coefficient including the actual clothing effect, based on the standard environment.

$$h_v = h_{co}F_{cleo} + h_rF_{cle} \tag{30}$$

The modified operative temperature OTV can be written in the following equation using TVF and ERFL.

$$\mathrm{OTV} = \frac{h_{co}F_{cleo}t_v + h_r F_{cle} t_r}{h_v} = t_a + \frac{\mathrm{TVF}}{h_v} + \frac{\mathrm{ERFL}}{h_v} \tag{31}$$

Thus, OTV can be expressed as the summation of air temperature and each effect of air movement and longwave radiation.

Replacing the dry heat loss of Eq (16) by that of Eq. (29), the total heat loss from the skin surface Q_{sk} can be expressed as follows:

$$\begin{aligned} Q_{sk} &= C + R_L + E \\ &= h_v(t_{sk} - \mathrm{OTV}) + wh_e'(p_{sk,s} - p_a) \end{aligned} \tag{32}$$

In the same manner as to HOT and ET*, the tradeoff between the modified operative temperature OTV and humidity is examined.

$$\begin{aligned} Q_{sk} &= h_v\left[\left(t_{sk} + \tfrac{wh_e'}{h_v}p_{sk,s}\right) - \left(\mathrm{OTV} + \tfrac{wh_e'}{h_v}p_a\right)\right] \\ &= h_v\left[\left(t_{sk} + \tfrac{wh_e'}{h_v}p_{sk,s}\right) - \left(\mathrm{HOTV} + \tfrac{wh_e'}{h_v}p_{\mathrm{HOTV},s}\right)\right] \\ &= h_v\left[\left(t_{sk} + \tfrac{wh_e'}{h_v}p_{sk,s}\right) - \left(\mathrm{ETV} + 0.5\tfrac{wh_e'}{h_v}p_{\mathrm{ETV},s}\right)\right] \end{aligned} \tag{33}$$

where HOTV (°C), $p_{\mathrm{HOTV},\,s}$ (kPa), and $p_{\mathrm{ETV},\,s}$ (kPa) are the corrected humid operative temperature (Horikoshi et al. 1991), saturated water vapor pressure at HOTV, and saturated water vapor pressure at ETV, respectively. HOTV reflects the combined effect of OTV and humidity, but is still defined at 100% relative humidity. ETV is converted from HOTV to indicate the temperature at 50% relative humidity, in the same manner to Gagge et al. (1971, 1986) who have converted HOT into ET*.

$$\mathrm{HOTV} = \mathrm{OTV} + \tfrac{wh_e'}{h_v}\left(p_a - p_{\mathrm{HOTV},s}\right) \tag{34}$$

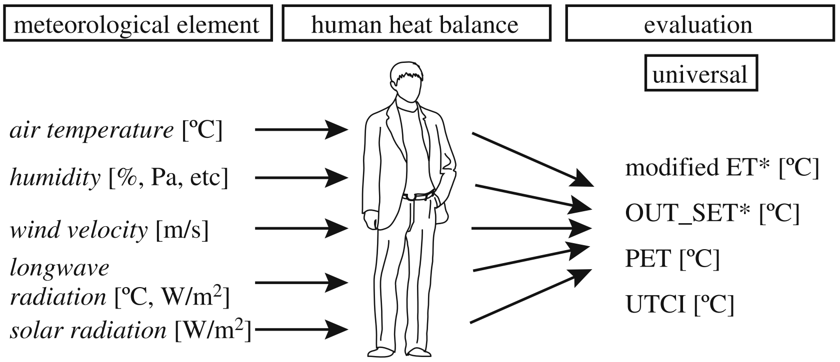
$$\begin{aligned} \mathrm{ETV} &= \mathrm{OTV} + \frac{wh_e'}{h_v}\left(p_a - 0.5p_{\mathrm{ETV},s}\right) \\ &= t_a + \frac{\mathrm{TVF}}{h_v} + \frac{\mathrm{ERFL}}{h_v} + \frac{\mathrm{EHF}}{h_v} \end{aligned} \tag{35}$$

$$\mathrm{EHF} = wh_e'\left(p_a - 0.5p_{\mathrm{ETV},s}\right) \tag{36}$$

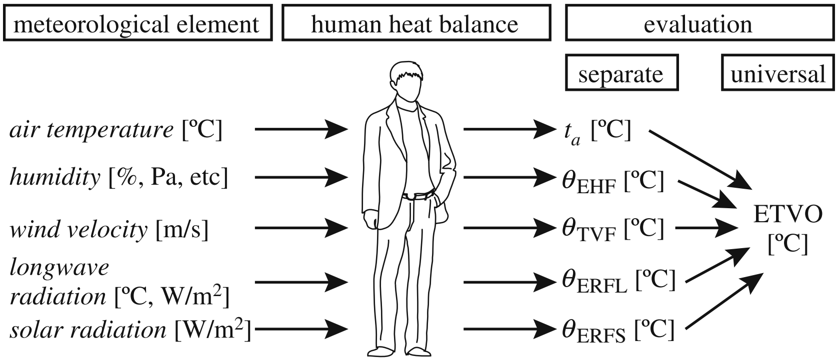
where EHF (W/m^2) indicates the separate effect of humidity, referring to 50% relative humidity, and is defined as the humid energy exchanged on the exposed body surface. This quantity is referred to as the effective humid field (Horikoshi et al. 1995).

As shown in Eq. (35), ETV is expressed as the summation of the air temperature plus the effective temperature differences caused by TVF, ERFL, and EHF.

Fig. 1 Outlines of previous and new indices



(a) Outline of previous indices



(b) Outline of ETVO

Each of these quantities refers to air movement, longwave radiation, and humidity, respectively. That is, ETV can describe the universal effect of environmental variables in itself and its separate effects simultaneously in the same unit of °C. This is the feature unique to ETV.

This paper proposes the new index for outdoors by adding the shortwave component of radiation, id est, solar radiation, to ETV without missing its feature. The authors tentatively call this newly derived index Outdoor ETV "ETVO". The dry heat loss in outdoors can be expressed by subtracting the net heat gain of solar radiation to the body R_S (W/m^2) from the heat loss of Eq. (29).

$$\begin{aligned} C + R_L - R_S &= h_v(t_{sk} - \mathrm{OTV}) - R_S \\ &= h_v(t_{sk} - \mathrm{OTVS}) \end{aligned} \tag{37}$$

$$\mathrm{OTVS} = \mathrm{OTV} + \frac{R_S}{h_v} = t_a + \frac{\mathrm{TVF}}{h_v} + \frac{\mathrm{ERFL}}{h_v} + \frac{\mathrm{ERFS}}{h_v} \tag{38}$$

$$\mathrm{ERFS} = R_S \tag{39}$$

The modified operative temperature OTVS (°C) can be expressed as the summation of air temperature and each effect of air movement, longwave radiation, and solar radiation. ERFS (W/m^2) indicates the effective temperature difference in air temperature caused by the heating power of solar radiation and is defined as the net solar energy exchanged on the exposed body surface. This paper refers to this quantity as the effective shortwave radiant field.

Replacing the dry heat loss of Eq. (32) by that of Eq. (37), the total heat loss from the skin surface Q_{sk} can be expressed as follows:

$$\begin{aligned} Q_{sk} &= C + R_L - R_S + E \\ &= h_v(t_{sk} - \mathrm{OTVS}) + wh_e'(p_{sk,s} - p_a) \end{aligned} \tag{40}$$

The tradeoff between the modified operative temperature OTVS and humidity is examined, in the same manner as for HOT and ET*, or as for HOTV and ETV.

$$\begin{aligned} Q_{sk} &= h_v\left[\left(t_{sk} + \tfrac{wh_e'}{h_v}p_{sk,s}\right) - \left(\mathrm{OTVS} + \tfrac{wh_e'}{h_v}p_a\right)\right] \\ &= h_v\left[\left(t_{sk} + \tfrac{wh_e'}{h_v}p_{sk,s}\right) - \left(\mathrm{HOTVS} + \tfrac{wh_e'}{h_v}p_{\mathrm{HOTVS},s}\right)\right] \\ &= h_v\left[\left(t_{sk} + \tfrac{wh_e'}{h_v}p_{sk,s}\right) - \left(\mathrm{ETVO} + 0.5\tfrac{wh_e'}{h_v}p_{\mathrm{ETVO},s}\right)\right] \end{aligned} \tag{41}$$

where HOTVS (°C), $p_{\mathrm{HOTVS},\,s}$ (kPa), and $p_{\mathrm{ETVO},\,s}$ (kPa) are a modification of HOTV proposed by Horikoshi et al. (1991) as adding to the solar effect, saturated water vapor pressure at HOTVS, and saturated water vapor pressure at ETVO, respectively. ETVO is converted from HOTVS, just like the conversion from HOT to ET*, or from HOTV to

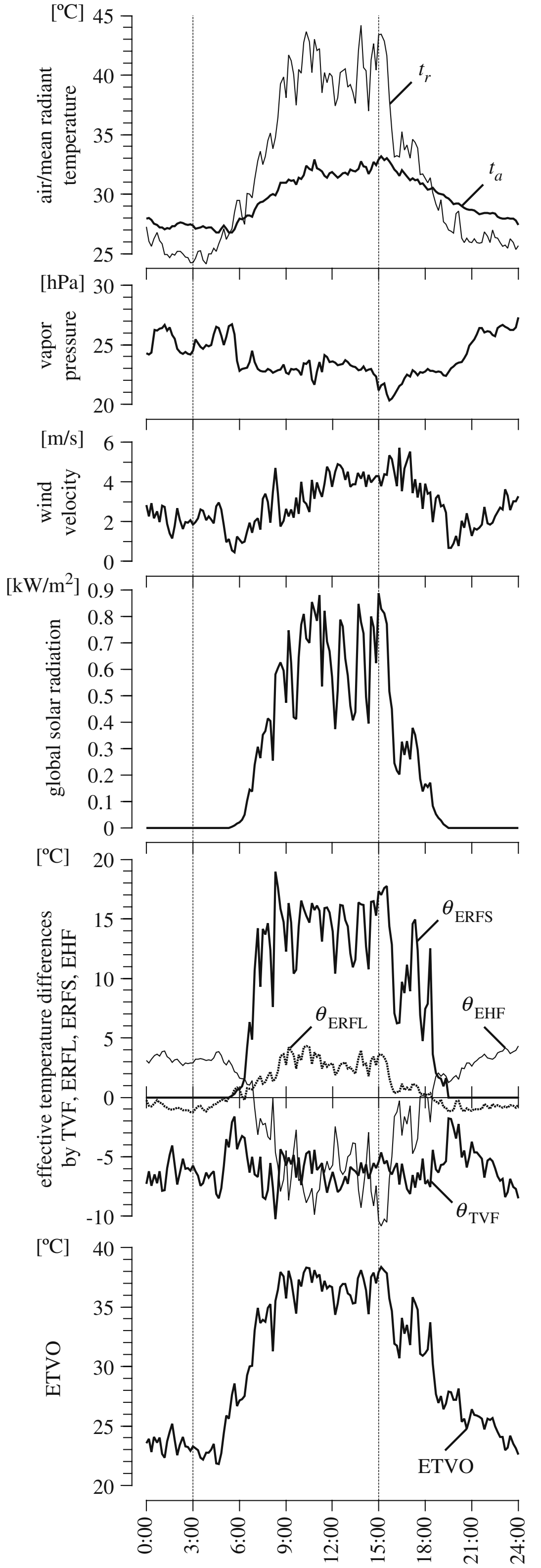


Fig. 2 Observed data and the calculation of ETVO on 13 July 2004

ETV. Thus, ETVO is defined as the hypothetical air temperature at 50% relative humidity that yields the same skin wettedness w and the same total heat loss from skin Q_{sk} as for the actual outdoor environment.

$$\begin{aligned}\mathrm{ETVO} &= \mathrm{OTVS} + \frac{wh'_e}{h_v}\left(p_a - 0.5p_{\mathrm{ETVO},s}\right)\\ &= t_a + \frac{\mathrm{TVF}}{h_v} + \frac{\mathrm{ERFL}}{h_v} + \frac{\mathrm{ERFS}}{h_v} + \frac{\mathrm{EHF}}{h_v}\\ &= t_a + \theta_{\mathrm{TVF}} + \theta_{\mathrm{ERFL}} + \theta_{\mathrm{ERFS}} + \theta_{\mathrm{EHF}}\end{aligned} \tag{42}$$

$$\mathrm{EHF} = wh'_e\left(p_a - 0.5p_{\mathrm{ETVO},s}\right) \tag{43}$$

where $\theta_{\mathrm{TVF}} = \mathrm{TVF}/h_v[^\circ\mathrm{C}]$, $\theta_{\mathrm{ERFL}} = \mathrm{ERFL}/h_v[^\circ\mathrm{C}]$, $\theta_{\mathrm{ERFS}} = \mathrm{ERFS}/h_v[^\circ\mathrm{C}]$, and $\theta_{\mathrm{EHF}} = \mathrm{EHF}/h_v[^\circ\mathrm{C}]$. Finally, ETVO is expressed as the summation of the air temperature plus the effective temperature differences caused by TVF, ERFL, ERFS, and EHF. Each of these quantities refers to air movement, longwave radiation, solar radiation, and humidity, respectively. In other words, this index is a modification of ETV proposed by Horikoshi et al. (1995) as adding to the solar effect, and keeps the feature of ETV which can describe both the combined effect of environmental variables and their separate effects.

Previous applications of ET* and SET* to outdoors

Several studies applied ET* (Umemura and Horikoshi 1991; Furuta and Horikoshi 2000), SET* (Umemura et al. 1993; Pickup and de Dear 2000; Mukai and Horikoshi 2002), and PMV (Umemura et al. 1993) to outdoor situations by means of the mean radiant temperature integrating the shortwave and longwave components. ISB (2009) also adopted the mean radiant temperature T_{mrt} (K), similar to that of those studies to derive the recent index UTCI as follows:

$$T_{mrt} = \left[\frac{1}{\sigma}\sum_{i=1}^{n}\left(L_i + \frac{a_h D_i}{\varepsilon}\right)\varphi_{i-h} + \frac{a_h f_p I_{dn}}{\varepsilon\sigma}\right]^{0.25} \tag{44}$$

where L_i (W/m^2), D_i (W/m^2), I_{dn} (W/m^2), a_h (n.d.), and f_p (n.d.) are longwave radiation from surrounding i, diffuse shortwave radiation from surrounding i, direct solar radiation, solar absorptivity of the clothed body, and projected area factor of the clothed body, respectively.

These indices by using this radiant temperature, however, can never indicate each effect of shortwave and longwave components of radiation separately. Apart from them, ET* or SET* can be modified by subtracting the net solar heat gain to the body R_S (W/m^2) from the heat loss of Eq. (8), just like ETVO is modified from ETV. The total dry heat loss in outdoors can be expressed as follows:

$$\begin{aligned}C + R_L - R_S &= h'(t_{sk} - \mathrm{OT}) - R_S\\ &= h'(t_{sk} - \mathrm{OTS})\end{aligned} \tag{45}$$

$$\mathrm{OTS} = \mathrm{OT} + \frac{R_S}{h'} \tag{46}$$

The modified operative temperature OTS (°C) indicates the operative temperature including solar effect.

From the total dry heat loss of Eq. (45) and the evaporative heat loss of Eq. (13), the total heat loss from the skin surface Q_{sk} (W/m^2) can be expressed as follows:

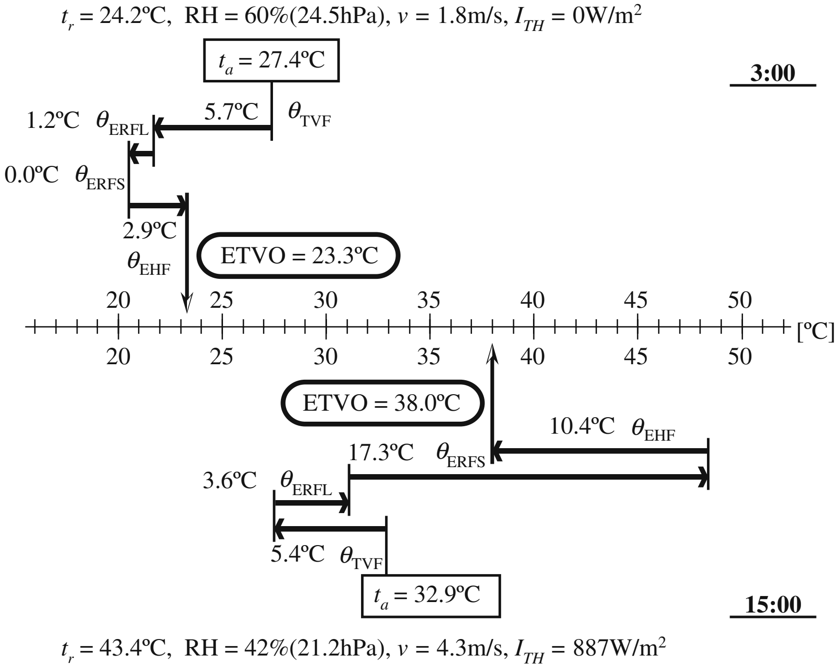
$$\begin{aligned}Q_{sk} &= C + R_L - R_S + E\\ &= h'(t_{sk} - \mathrm{OTS}) + wh'_e\left(p_{sk,s} - p_a\right)\end{aligned} \tag{47}$$

In the same manner as for the original ET*, the tradeoff between the modified operative temperature OTS and

Table 1 Observed data and the calculation of ETVO and the other indices

Date/Time	13 July 2004 03:00a.m.	13 July 2004 15:00 p.m.
Air temperature	27.4°C	32.9°C
Mean radiant temperature	24.2°C	43.4°C
Relative humidity (vapor pressure)	67% (24.5 hPa)	42% (21.2 hPa)
Velocity	1.8 m/s	4.3 m/s
Global solar radiation	0 W/m^2	887 W/m^2
ETVO	ETVO=23.3°C	ETVO=38.0°C
	θ_{TVF}=–5.7°C	θ_{TVF}=–5.4°C
	θ_{ERFL}=–1.2°C	θ_{ERFL}=3.6°C
	θ_{ERFS}=0.0°C	θ_{ERFS}=17.3°C
	θ_{EHF}=2.9°C	θ_{EHF}=–10.4°C
Modified ET*	27.6°C	37.4°C
Modified SET* (OUT_SET*)	23.4°C	33.3°C
UTCI	27.1°C	35.6°C

Fig. 3 Sequential expression of effects of each meteorological element on thermal feeling from t_a to ETVO



humidity is examined in order to derive the modified ET*, described as ETO in the equations of this paper.

$$\begin{aligned} Q_{sk} &= h'\left[\left(t_{sk} + \frac{wh'_e}{h'}p_{sk,s}\right) - \left(\mathrm{OTS} + \frac{wh'_e}{h'}p_a\right)\right] \\ &= h'\left[\left(t_{sk} + \frac{wh'_e}{h'}p_{sk,s}\right) - \left(\mathrm{ETO} + 0.5\frac{wh'_e}{h'}p_{\mathrm{ETO},s}\right)\right] \end{aligned} \tag{48}$$

$$\begin{aligned} \mathrm{ETO} &= \mathrm{OTS} + \frac{wh'_e}{h'}\left(p_a - 0.5p_{\mathrm{ETO},s}\right) \\ &= t_a + \frac{\mathrm{ERFL}}{h'} + \frac{\mathrm{ERFS}}{h'} + \frac{\mathrm{EHF}_{\mathrm{ETO}}}{h'} \end{aligned} \tag{49}$$

$$\mathrm{EHF}_{\mathrm{ETO}} = wh'_e\left(p_a - 0.5p_{\mathrm{ETO},s}\right) \tag{50}$$

where $p_{\mathrm{ETO},\ s}$ (kPa) is saturated water vapor pressure at ETO.

ETO can indicate separately each effect of shortwave and longwave radiation, as well as humidity effect. As shown in Eq. (49), however, there is no independent term related to the wind velocity, and the coefficient h' is defined by a function of the wind velocity. Therefore, the second, third and fourth terms on the right side of Eq. (49), which refer to longwave radiation, solar radiation and humidity, respectively, depend on the wind velocity. Even so, it is still difficult to use this index for expressing the effect of individual thermal environmental variables. In contrast, since the coefficient h_v is independent of the wind velocity, the index ETVO can derive much more information, i.e., the independent effect of each environmental variable as well as the universal effect. Generally, the effect of air movement is larger in outdoor situations. Thus, the index ETVO is more useful than the modified ET* for outdoors, as well as the other indices mentioned above.

Outlines of the previous and new indices are illustrated in Fig. 1.

Calculation of ETVO

This paper calculates ETVO based on the data observed on the roof of a building in Fukuoka city of Japan during a

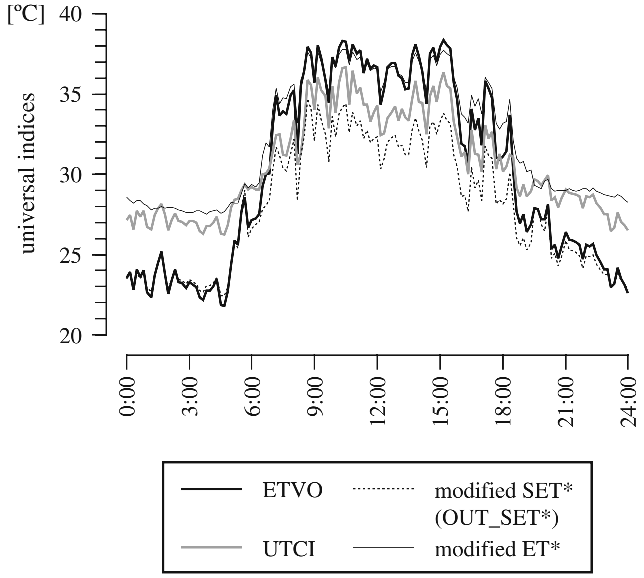


Fig. 4 Comparison of universal indices by data observed on 13 July 2004

summer day. The observed items were air temperature and humidity by thermohygrometer (T&D TR-72S) installed in the screen, wind velocity by anemometer (YOUNG CYG-3002), and shortwave and longwave radiation fluxes by four-component radiometer (EKO MR-40). The walking metabolic rate of 2.0 met, summer clothing insulation of 0.4 clo, the solar absorptivity of the clothed body of 0.3 (Shinohara and Tokumoto 1999; Watanabe et al. 2008) were adopted as constant. The mean skin temperature and skin wettedness were estimated by the two-node model (Gagge et al. 1986; Fobelets and Gagge 1988). The projected area factor of the clothed body, the diffuse radiation fraction for global solar radiation, and the convective heat transfer coefficient were estimated by Miyamoto et al. (1998), Udagawa and Kimura (1978), and Kuwabara et al. (2001), respectively.

Figure 2 shows the observed values and the calculated results of ETVO. Table 1 and Fig. 3 show the excerpts from data at 3:00 a.m. and 15:00 p.m. of Fig. 2. As shown in Fig. 2, the difference θ_{TVF} indicates the negative consistently, and smaller as the velocity is larger. The difference θ_{ERFS} indicates much larger in the daytime and zero while no solar radiation is observed in the nighttime. The difference θ_{ERFL} is approximately from a third to a fourth of the θ_{ERFS} in the daytime and indicates the negative in the nighttime in which t_r is lower than t_a. As shown in Table 1 and Fig. 3, at 3:00 a.m., the largest effective temperature difference is caused by TVF and wind velocity has the bigger contribution to the fall in ETVO, while solar radiation has no effect on ETVO. In contrast, at 15:00 p.m., the largest effective temperature difference is caused by ERFS. Its warming effect, that is θ_{ERFS}, is larger than three times as large as the cooling effect of wind θ_{TVF}. Air temperature at 15:00 p.m. is 5.5°C higher than that at 3:00 a.m. although wind velocity is 2.5 m/s larger, then the wind effect is similar to that at 3:00 a.m.. As for longwave radiation, the warming effect at 15:00 p.m. is three times as large as cooling effect at 3:00 a.m. but smaller than wind, solar radiation, and humidity. Longwave radiation reduces ETVO by 1.2°C at 3:00 a.m. but raises it by 3.6°C at 15:00 p.m..

Figure 4 shows calculated results of ETVO, UTCI, OUT_SET*, and modified ET*. ETVO in the daytime which are similar to modified ET* and larger than the other indices, but in the nighttime ETVO is similar to modified SET* (OUT_SET*) and contrastingly smaller than the other indices. UTCI shows approximately midway between ETVO and modified SET* in the daytime, and similar to modified ET* in the nighttime. Most of these differences among the indices depend on their own standard environments that the indices adopt, and not so much on their accuracy for human thermal feelings since all these indices are based on the human heat balance.

Conclusion

The separate indices θ_{TVF}, θ_{ERFL}, θ_{ERFS}, and θ_{EHF} can be compared directly with each other since all the values are derived as the temperature differences from the air temperature in the same unit of °C. Therefore, the calculation of ETVO that simultaneously derives these separations helps us to understand how much each factor affects the thermal feeling during the given environmental conditions. On the other hand, the calculation of modified ET*, OUT_SET*, UTCI, and the other indices for the outdoors, derives only universal effect and gives no information about each factor. Here again, the universal ETVO has specific and advanced features that means its derivation is accompanied by separate indices for each factor.

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International Society of Biometeorology (2009) www.utci.org/

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