Title

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Application of Gagge's energy balance model to determine humidity-dependent temperature thresholds for healthy adults using electric fans during heatwaves

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ABSTRACT

Heatwaves are one of the most dangerous natural hazards causing more than 166,000 deaths from 1998–2017. Their frequency is increasing, and they are becoming more intense.

Electric fans are an efficient, and sustainable solution to cool people. They are, for most applications, the cheapest cooling technology available. However, many national and international health guidelines actively advise people not to use them when indoor air temperatures exceed the skin temperature, approximately 35 °C.

We used a human energy balance model, to verify the validity of those recommendations and to determine under which environmental (air temperature, relative humidity, air speed and mean radiant temperature) and personal (metabolic rate, clothing) conditions the use of fans would be beneficial.

We found that current guidelines are too restrictive. Electric fans can be used safely even if the indoor dry-bulb temperature exceeds 35 °C since they significantly increase the amount of sweat that evaporates from the skin. The use of elevated air speeds (0.8 m/s) increases the critical operative temperature at which heat strain is expected to occur by an average of 14 °C for relative humidity values above 22 %. We also analyzed the most extreme weather events from 1990 to 2014 recorded in the 115 most populous cities worldwide, and we determined that in 93 of them the use of fans would have been beneficial.

We developed a free, open-source, and easy-to-use online tool to help researchers, building practitioners, and policymakers better understand under which conditions electric fans can be safely used to cool people.

1. Introduction

The World Meteorological Organization (WMO) and World Health Organization (WHO) describe heatwaves as: "periods of unusually hot and dry or hot and humid weather that have a subtle onset and cessation, a duration of at least two or three days, usually with a discernible impact on human and natural systems" [1]. Heatwaves impact various sectors differently, hence, there is not a universal standardized scientific definition [2]. Global climate change is predicted to cause peak phenomena like heatwaves to increasing in length, intensity, and frequency [3]. A wide range of factors can increase health risks during heatwaves, including individual physiological differences, demographics (e.g., age), socioeconomic characteristics (e.g., income, homelessness), pre-existing health conditions, prolonged outdoor activities, and social isolation [1]. Heatwaves also place an additional burden on the health, emergency, energy, water, and transportation sectors. For example, during heatwaves peak electricity demand increases due to increased demand for cooling, while the efficiency of the grid and power generation decreases. The International Energy Agency (IEA) estimated that in 2016 the energy required for cooling during heatwaves accounted for more than 70 % of residential consumption in regions such as the Middle East and some parts of the U.S. [4]. Such increased demand can cause power shortages and blackouts, which can cripple the water supply system as it happened in Pakistan in 2015. This heatwave claimed more than 700 lives and hospitals had to cope with an increased number of people suffering from heatstroke and dehydration [5].

The IEA estimated that in 2016 approximately 2.8 billion people lived in the hottest parts of the world, and only 8 % of them had compressor-based air conditioners installed in their homes, compared to 90 % ownership in the U.S. and Japan [4]. While the former

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Nomenclature

α	fraction of the total body mass considered to be thermally in the skin compartment
σ	Stefan–Boltzmann constant, (5.67 x 10^{-8} W/(m^{2}K^2))
ε	average emissivity of clothing or body surface
A_{body}	body surface area, (m^2)
A_r	effective radiation area of the body, (m^2)
$C + R$	sensible heat loss from skin, (W/m^2)
C_{res}	rate of convective heat loss from respiration, (W/m^2)
c_{sw}	driving coefficient for regulatory sweating, (g/(hKm^2))
E_{dif}	rate of evaporative heat loss from moisture diffused through the skin, (W/m^2)
E_{max}	maximum rate of evaporative heat loss from skin, (W/m^2)
E_{res}	rate of evaporative heat loss from respiration, (W/m^2)
E_{rsw}	rate of evaporative heat loss from sweat evaporation, (W/m^2)
E_{sk}	total rate of evaporative heat loss from skin, (W/m^2)
f_{cl}	clothing area factor A_{cl}/A_{body}, (m^{2}K/W)
h	sum of convective h_c and radiative h_r heat transfer coefficients, (W/(m^{2}K))
h_c	convective heat transfer coefficient, (W/(m^{2}K))
h_e	evaporative heat transfer coefficient, (W/(m^{2}kPa))
h_r	linear radiative heat transfer coefficient, (W/(m^{2}K))
$height$	body height, (m)
i_{cl}	permeation efficiency of water vapor through the clothing layer
I_{cl}	total clothing insulation, (clo)
M	rate of metabolic heat production, (W/m^2)
m_{bl}	skin blood flow, (L/(hm^2))
m_{rsw}	rate at which regulatory sweat is generated, (mL/h^2)
$mass$	body mass, (kg)
p_a	water vapor pressure in ambient air, (kPa)
$p_{sk,s}$	water vapor pressure at skin, (kPa)
q_{res}	total rate of heat loss through respiration, (W/m^2)
q_{sk}	total rate of heat loss from skin, (W/m^2)
R_{cl}	thermal resistance of clothing, (m^{2}K/W)
$R_{e,cl}$	evaporative heat transfer resistance of clothing layer, (m^{2}kPa/W)
RH	relative humidity, (%)
S	rate of heat storage in the human body, (W/m^2)
S_{cr}	rate of heat storage in the core compartment, (W/m^2)
S_{sk}	rate of heat storage in the skin compartment, (W/m^2)
t_{cl}	clothing temperature, (°C)
$t_{cr,n}$	neutral core mean temperature, (°C)
t_{cr}	core mean temperature, (°C)
t_{db}	dry-bulb air temperature, (°C)
t_o	operative air temperature, (°C)
$\overline{t_r}$	mean radiant temperature, (°C)
t_{re}	rectal temperature, (°C)
$t_{sk,n}$	neutral skin mean temperature, (°C)
t_{sk}	skin mean temperature, (°C)
t_{wb}	wet-bulb air temperature, (°C)
V	average air speed, (m/s)
w	skin wettedness
w_{max}	skin wettedness practical upper limit
CDC	Centers for Disease Control and Prevention
EPA	United States Environmental Protection Agency
IEA	International Energy Agency
NOAA	National Oceanic and Atmospheric Administration
PHS	Predicted Heat Strain
SET	Standard Effective Temperature, (°C)
UN	United Nations
WHO	World Health Organization
WMO	World Meteorological Organization

percentage is expected to grow rapidly in the coming years as income levels rise, it is clear that accessible alternatives to compressor-based air conditioning for personal cooling are an urgent priority [6]. Mass air conditioning use in the future will exert further pressure on electricity grids and exacerbate global greenhouse gas emissions due to the increase in energy consumption [4]. Moreover, the United States Environmental Protection Agency (EPA) estimates that globally 25 % of hydrofluorocarbons with high global warming potential are emitted by residential and commercial air conditioning equipment, and hydrofluorocarbons emissions in developing nations are projected to quadruple by 2030 [7].

Increasing air movement is a personalized cooling strategy that bypasses the issues associated with refrigerant gases and is more efficient than compressor-based air conditioning [8]. Electric fans are relatively inexpensive (for example, a basic model can be purchased for 10 USD in India), energy-efficient, some (e.g., pedestal and desk) do not have any installation cost, and with direct current motors, they now consume single-digit watts and provide substantial air flows [9]. The relatively low electricity consumption and cost of fans could help mitigating additional negative compounding health factors such as socioeconomic inequality or poor access to air conditioning [8]. Electric fans can be used either as an alternative cooling technology or in combination with a reduced level of compressor-based air conditioning [10–12]. They are also effective at increasing the thermal satisfaction of occupants even in tropical hot and humid climates [13].

In 2016, an estimated 2.3 billion electric fans were in use worldwide and they remain the most common form of cooling in households [4]. It is estimated that one in two households own at least one fan and there are twice as many fans as air conditioners in use worldwide, although this ratio is declining rapidly [4]. In 2016, the IEA estimated that electric fans accounted for 1.5 % of total residential energy consumption worldwide, and their energy use has increased 3.6 times between 2000 and 2016 [4]. The overall household energy consumption could, however, sharply increase if people start replacing them with air conditioners. Air conditioners consume significantly more energy than electric fans and can negatively impact climate change when refrigerants are leaked into the atmosphere [4].

Excessive heat can compromise the ability to maintain core temperature within safe limits and can worsen the health of those with pre-existing health conditions [1]. For example, people with cardiovascular disease are at an elevated risk of catastrophic collapse due to an exacerbation of cardiovascular strain associated with the maintenance of central blood pressure in the face of rising skin blood flow sometimes accompanied by decreases in blood volume due to dehydration [8].

The WHO and the WMO together with national government agencies provide public health guidance for people to minimize heat stress during heatwaves. For example, they suggest keeping the body hydrated and out of the heat, and keeping the home cool. However, the WHO also states that if the t_{db} is higher than 35 °C fans can make an individual hotter and “fans should be discouraged unless they are bringing in significantly cooler air” [1]. They also mention that when t_{db} is higher than 35 °C, fans may not prevent heat-related illness [14]. This is possibly because if t_{db} exceeds t_{sk} (approximately 35 °C) the gradient for dry heat loss is reversed and sensible heat is added to the body. Ready.gov, a national public service campaign of the U.S. Government that aims to “educate and empower the American people to prepare for, respond to and mitigate emergencies, including natural and man-made disasters”, states that electric fans should not be used when outside temperatures are higher than 35 °C [15]. According to Ready.gov, in these conditions electric fans could increase the risk of heat-related illness, and that they create airflow and a false sense of comfort, but do not reduce body temperature. The Centers for Disease Control and Prevention (CDC) states that when the temperature is in the high 90’s (°F, i.e., above 32 °C) fans will not prevent heat-related illness [16]. Similarly, the EPA Excessive Heat Events Guidebook discourages directing the flow of fans towards the body when t_{db} is higher than 32.2 °C [17].

The above recommendations underestimate the evaporative cooling effect of electric fans, ignoring research evidence that healthy adults do in fact benefit from their use when t_{db} is higher than the t_{sk} [10,18–20] possibly discouraging some people to use the only cooling option that they have available. It should also be noted that guidelines such as those provided by Ready.gov, may further worsen conditions for many since they do not only state that fans may not help to prevent heat strain but they also encourage people to turn them off when outside temperatures are higher than 35 °C. This not only encourages people to turn electric fans off when their use is still beneficial but is illogical in that fans should not be controlled as a function of the outdoor temperature but solely on indoor environmental conditions. Indoor temperatures are influenced by outdoor conditions but are often different than outdoor temperatures. The use of electric fans is beneficial, even when t_{db} exceeds t_{sk}, because fan airflow increases the amount of heat that the body can dissipate to the environment via the evaporation of sweating [19,21]. This applies even at high RH since fans help sweat, which otherwise would either sit on the skin or drip off the body, to evaporate. The maximum t_{db} at which electric fans should be used will depend on the RH, as shown in several experimental studies listed below.

Ravanelli et al. [18] conducted a laboratory experiment comprising eight healthy males and concluded that electric fans help in preventing heat-related elevation in heart rate and t_{cr} in both of the following conditions t_{db}=42 °C and RH=50 %, and t_{db}=36 °C and RH=80 %. Morris et al. [22] also obtained similar results in an experimental study conducted in laboratory settings. Their experiment, comprising 12 healthy men, concluded that when t_{db}=47 °C and RH=15 % fan use is not advisable. On the other hand, for values of t_{db}=40 °C and RH=51 % fans reduced core temperature and cardiovascular strain and improved thermal comfort [22]. It should be noted that the enthalpy of the air in the latter condition was considerably higher (102.0 kJ/kg) than in the former condition (73.0 kJ/kg). At 47 °C and 15 % RH heat strain was a risk because all the sweat could evaporate, even without the use of elevated air movement, and air movement in those conditions only increases convective heat gain without increasing evaporative heat loss. In hot and dry conditions, skin wetting or evaporative cooling of the air can be used to respectively increase latent heat loss from the skin or to reduce t_{db} and its associated sensible heat gains. Skin-wetting has been shown to reduce physiological heat strain, dehydration, and thermal discomfort at temperatures up to 47 °C, irrespective of RH [23]. Evaporative cooling is an isoenthalpic process that causes a drop in t_{db} proportional to the sensible heat drop and an increase in humidity ratio proportional to the latent heat gain. For example, evaporative cooling could have been used to economically and efficiently cool the air from t_{db}=47 °C and RH=15 % to either t_{db}=40 °C and RH=28.0 % or to t_{db}=30 °C and RH=63.0 %. Under such conditions, the heat stress on occupants would be even lower than in the condition tested in Morris et al. [22] experiment and consequently, participants would not have experienced heat strain. Gagnon et al. [20] exposed nine young (26 ± 3 yr; range 21–30, five men and four women) and nine aged (68 ± 3 yr; range 61–72, three men and six women) healthy adults to t_{db}=42 °C, a temperature significantly higher than t_{sk}. The RH was gradually increased throughout the course of the experiment from 30 % to 70 %. They observed that both heart rate and t_{cr} in the aged, but not in the young, were higher with fan use compared to the baseline condition (i.e., no fan use) due to the well-described impairments in thermoregulatory sweating with age. It should be noted that the temperature tested in this study was significantly higher than t_{sk}. More experimental research is needed to determine how electric fan use affects aged adults in the temperature range from 35 °C to 42 °C.

Based on this evidence, advising healthy adults not to use fans when t_{db} exceed t_{sk} or 35 °C could increase their risk of suffering from heat strain and would prevent them from using an effective, energy-efficient, and low-cost cooling technology. To better understand under which environmental conditions (i.e., t_{db}, RH) the use of fans would be beneficial, both Jay et al. [19] and Morris et al. [8] developed a simplified heat balance model. They then used their model to develop a chart that can be used to assist public health messaging in explaining to young and older adults when the use of electric fans is beneficial to cool the human body. They concluded that the use of electric fans is beneficial even when t_{db} exceeds t_{sk}. Their model can be further improved allowing the user to change the value of rate of metabolic heat production (M) or total clothing insulation (I_{cl}), estimate iteratively t_{sk} and t_{cr}, consider radial asymmetry, and adjust air speed. Jay et al. [19] chose a value of 4.5 m/s based on measured values of air speed at a distance of 1.0 m of an 18" pedestal fan set at maximum speed [19]. Morris et al. [8] chose instead a value of 3.5 m/s. Their results may be difficult to generalize since such high air speeds cannot be easily achieved by most ceiling fans [24], pedestal, or desk fans [9] available on the market.

To this end, we used the human thermoregulatory model developed by Gagge et al. [25] to estimate heat losses and physiological variables as a function of environmental and personal factors [26]. The model originally outputs the Standard Effective Temperature (SET) that allows the combined effects of t_{db}, RH, mean radiant temperature ($\overline{t_r}$), V, I_{cl}, M to be reduced to a standard environment. Among its attributes are modeling of the physiology of sweating and the effects of air movement on sensible and evaporative heat transfer. ASHRAE Standard 55 uses this model to determine the effects of elevated air speeds on body heat balance and thermal comfort [27]. The model has also been tested for its relevance under realistic air flows and V produced by different types of fans, such as partial immersion in the elevated flows, and flows with different turbulence intensity [28]. This makes the SET model appropriate for predicting the thermophysiological effects of elevated air speed during heatwaves and to determine humidity-dependent temperature thresholds at which electric fans would become detrimental. We compared our results with those obtained from the PHS model [29,30]. Which allows the analytical evaluation of the thermal stress experienced by a subject working in a hot environment. We contextualized our results by comparing them to the most extreme weather events recorded in the 115 most populous cities worldwide.

Finally, to help policymakers and people worldwide we chose to incorporate the model into the CBE Thermal Comfort Tool [31] and the Python package `pythermalcomfort` [32]. The former is an open-source, free-to-use, web-based online tool that provides interactive plots and displays the results to the user (https://comfort.cbe.berkeley.edu). The latter is a Python package that allows users to calculate the most common thermal comfort indices in compliance with the main thermal comfort standards. Our tools should allow users to determine when people can safely use elevated air speeds to cool themselves.

2. Methodology

The energy balance model we used estimates how environmental (t_{db}, $\overline{t_r}$, V, RH) and personal factors (I_{cl}, M) influence both latent and sensible components of the total rate of heat loss from skin (q_{sk}), and the total rate of heat loss through respiration (q_{res}). Moreover, it can be used to estimate the value of some physiological variables such as t_{sk}, and t_{cr}. In non-uniform environments t_{db} and V are assumed to be equal to the average temperature and air speed measured at 0.1, 0.6, and 1.1 m height for seated occupants and at 0.1, 1.1, and 1.7 m for standing occupants.

Section 2.1 describes the main Equations used by the model to derive the results.

2.1. Energy balance

The human body exchanges both sensible and latent heat with its surrounding environment. Heat gain or loss from the human body to its environment can be expressed as a function of environmental and personal factors [33]. Sensible heat is transferred via conduction, convection and radiation ($C + R + C_{res}$). Latent heat loss occurs from the evaporation of sweat (E_{rsw}), moisture diffused through the skin (E_{dif}), and respiration (E_{res}). The energy balance in the human body is described by:

$$M - W = C + R + E_{sk} + C_{res} + E_{res} + S_{sk} + S_{cr} \tag{1}$$

This equation assumes that the body comprises two main thermal compartments: the skin and the core. If the exogenous and endogenous heat gains cannot be compensated by heat loss, then both the S_{sk}, and the S_{cr} increase and in turn the t_{sk}, and t_{cr} rise, respectively. One of the main differences between Gagge et al. [25] model and the one used by Jay et al. [19] is that Jay et al. [19] does not account for heat stored in the core or the skin compartment; hence, they assume the values of t_{sk} and t_{cr} to be constant. Calculating how t_{sk} and t_{cr} vary as a function of different environmental and personal factors allows us to better predict how much heat the body exchanges with its surrounding environment [33]. It should be noted that the steady-state model proposed by Jay et al. [19] is more conservative since it assumes a constant value for t_{sk}, overestimating the sensible heat gains when t_{db} exceeds t_{sk}. The equations used to determine sensible and latent heat loss are based on fundamental heat transfer theory, while the coefficients were estimated empirically [33].

2.1.1. Body surface area

All the terms presented in Eq. (1) are reported in power per unit of human body surface area (A_{body}). Eq. (2) can be used to estimate A_{body} as a function of the body mass ($mass$) and body height ($height$) [34].

$$A_{body} = 0.202 mass^{0.425} height^{0.725} \tag{2}$$

In thermal comfort research, this value is generally assumed to be constant and equal to 1.8 m^2. A recent detailed review paper concluded that most of the proposed equations in the literature were in agreement with each other to estimate A_{body} for adults with a healthy weight and standard physique [35].

2.1.2. Sensible heat loss from skin

Sensible heat loss from the human body mainly occurs from convection and radiation from the skin to the environment. The total amount of $C + R$ can be described as a function of t_{sk}, t_o, thermal resistance of clothing (R_{cl}), clothing area factor A_{cl}/A_{body} (f_{cl}), and sum of convective h_c and radiative h_r heat transfer coefficients (h). The equation can be expressed as:

$$C + R = \frac{t_{sk} - t_o}{R_{cl} + 1/\left(f_{cl} h\right)} \tag{3}$$

$$f_{cl} = 1.0 + 0.31 I_{cl} \tag{4}$$

$$h = h_c + h_r = \max(3.0, 8.6V^{0.53}) p_{atm}^{0.53} + 4\varepsilon\sigma \frac{A_{\mathrm{r}}}{A_{body}} \left[273.2 + \frac{\left(t_{\mathrm{cl}} + \overline{t_r}\right)}{2}\right]^3 \tag{5}$$

Where the ratio between effective radiation area of the body (A_r) and A_{body} is assumed to be 0.70 for a sitting person and 0.73 for a standing person [36]. The average emissivity of clothing or body surface (ε) is close to unity (typically 0.95) and the Stefan–Boltzmann constant (σ) is a constant. The value of t_o varies as a function of the convective heat transfer coefficient (h_c), linear radiative heat transfer coefficient (h_r), $\overline{t_r}$ and t_{db}, and it is described by:

$$t_o = \frac{h_r \bar{t}_r + h_c t_{db}}{h_r + h_c} \tag{6}$$

In Gagge et al. [25] model, the value of t_{sk} is calculated iteratively since it varies as a function of the heat loss from the human body towards its environment and the heat transferred from the core to the skin node. clothing temperature (t_{cl}) can be calculated as a function of t_o, t_{sk}, R_{cl} and the resistance of the air layer. As previously stated, it should be noted that this is not a conservative approach and in some circumstances, it may underestimate the value of $C + R$.

2.1.3. Latent heat loss from skin, (E_{sk})

The total rate of evaporative heat loss from skin (E_{sk}) comprises two terms: the rate of evaporative heat loss from sweat evaporation (E_{rsw}) and the rate of evaporative heat loss from moisture diffused through the skin (E_{dif}). E_{sk} depends on the w, water vapor pressure at skin ($p_{sk,s}$) normally assumed to be that of saturated water vapor at t_{sk}, water vapor pressure in ambient air (p_a), f_{cl}, evaporative heat transfer coefficient (h_e), and evaporative heat transfer resistance of clothing layer ($R_{e,cl}$).

$$E_{sk} = E_{rsw} + E_{dif} = \frac{w\left(p_{sk,s} - p_a\right)}{R_{e,cl} + 1/\left(f_{cl} h_e\right)} \tag{7}$$

Although Eq. (7) is expressed as a function of w, the human body does not regulate w directly but, rather, it regulates the m_{rsw}. The value of m_{rsw} can be predicted by the deviation of t_{sk} and t_{cr} from their set neutral value, and it is described by:

$$m_{rsw} = c_{sw}((1 - \alpha)(t_{cr} - t_{cr,n}) + \alpha(t_{sk} - t_{sk,n})) \exp(\frac{t_{sk} - t_{sk,n}}{10.7}) \tag{8}$$

Where the driving coefficient for regulatory sweating (c_{sw}) is assumed to be equal to 170 g/(hKm^2), the neutral core mean temperature ($t_{cr,n}$) is equal to 36.8 °C and neutral skin mean temperature ($t_{sk,n}$) is equal to 33.7 °C. The values of t_{sk} and t_{cr} are calculated iteratively by solving the heat balance equation. The fraction of the total body mass considered to be thermally in the skin compartment (α) is determined using:

$$\alpha_{sk} = 0.0418 + \frac{0.745}{m_{bl} - 0.585} \tag{9}$$

Skin wettedness varies as a function of the activity of the sweat glands and the environmental conditions. It correlates with warm discomfort and is a good measure of thermal stress. While w can theoretically range from 0 to 1, in most situations, the upper limit of

w is lower than 1 [33]. Gagge et al. [25] used the following equations to determine w_{max} for healthy and acclimatized humans:

$$w_{max} = \begin{cases} 0.38V^{-0.29} & \text{if } I_{cl} = 0 \\ 0.59V^{-0.08} & \text{if } I_{cl} > 0 \end{cases} \quad (10)$$

On the other hand, Jay et al. [19] adjusted the value of w_{max} based on fan use and age. For young adults, they assumed w_{max} to be equal to 0.65 for the 'fan on' condition and 0.85 for the 'fan off' condition. These values are higher than those estimated by the Gagge et al. [25] model.

2.1.4. Respiratory losses, (q_{res})

The human body exchanges both sensible and latent heat with its environment. The total rate of heat loss through respiration (q_{res}) equals the sum of the rate of convective heat loss from respiration (C_{res}) and the rate of evaporative heat loss from respiration (E_{res}). The value of q_{res} is can be determined using the following simplified equation [33]:

$$q_{res} = C_{res} + E_{res} = 0.0014M(34 - t_a) + 0.0173M(5.87 - p_a) \quad (11)$$

2.2. Data analysis

The heat balance model was used to estimate sensible and latent heat loss and several physiological parameters (e.g., m_{rsw}, t_{cr}). We will be referring to 'still air' condition when air velocities are below V=0.2 m/s [27]. This allowed us to compare our results with those obtained by Jay et al. [19]. We assumed $\overline{t_r}$ to be equal to t_{db}, I_{cl}=0.5 clo, and M=1.1 met, unless otherwise specified. It could be argued that some people during heatwaves may be wearing much less clothing than that, hence, a value of I_{cl} equal to 0.36 clo (i.e., walking shorts, short-sleeve shirt, underwear, socks, and shoes) would be more appropriate, however, we wanted to use a more conservative value. Results for different combinations of environmental and personal conditions can be generated using our online tool. In this manuscript, we assumed the permeation efficiency of water vapor through the clothing layer (i_{cl}) to be constant and equal to 1 and 0.45 [25], for naked and clothed people, respectively. Users can, however, change this value in the source code. We report heat losses per unit of skin surface area. Thermal strain is assumed to occur when either of the following parameters reaches their maximum value: w, skin blood flow, or m_{rsw}. The former assumption is based on the fact that there is a w_{max} for healthy and acclimatized humans [33]. The other two assumptions are based on the fact that Gagge et al. [25] state that serious danger of fatality exists when blood flow from the core to the skin is maximal or sweating reaches its maximum. Differently from Gagge et al. [25] we assumed the maximum blood flow from the core to the skin to be 80 L/(hm^2) and not 90 L/(hm^2). We selected this value since we wanted to limit the proportion of resting normothermic cardiac output going to the skin to be 40 % (for blood pressure maintenance) of the resting value for an adult male 6 L/(hm^2) [25]. We assumed that the use of electric fans is detrimental when the value of t_{cr} calculated for values of V higher than 0.2 m/s exceeds the value determined for the 'still air' condition. In addition, we recommend that fans should be turned off for temperatures (irrespective of RH) higher than the value of t_{db} at which the thermal heat strain curve at elevated air speeds intersects the for 'still air' condition.

Results were calculated using the `pythermalcomfort` Python package [32]. Lines in Figs. 2, 3, 4(a), 4(b), 7, and A.10 were smoothed using the `Scipy` function `ndimage.gaussian_filter1d`. We developed a tool that can be used to generate interactive figures that show the environmental conditions under which the use of elevated air speeds is beneficial. This tool has been added and integrated into the CBE Thermal Comfort Tool [31].

2.3. Predicted heat strain model

We also compared our results with those obtained from the PHS model that can be used to determine the thermal stress experienced by a subject in a hot environment. It allows to calculate the m_{rsw} and rectal temperature (t_{re}) that the human body will develop in response to the working conditions [29,30]. The PHS model has been validated based on a database including 747 lab experiments and 366 field experiments, from 8 research institutions [29]. It has not been validated for metabolic rates lower than 1.7 met (100 W/m^2), t_{db} higher than 50 °C and water vapor partial pressure (p_a) higher than 4 kPa (i.e., humidity ratio of 0.026 kg$_{water}$/kg$_{dryair}$). In this present study we are determining when fans should be used by individuals with a M=1.1 met, hence, we used the PHS model outside its ranges of validity. We calculated the PHS using the `pythermalcomfort` Python package [32] function `phs`. We assumed that elevated air speed is detrimental when the maximum allowable exposure time for heat storage estimated with a V=0.8 m/s is higher than the value estimated with a V=0.2 m/s.

2.4. Weather data

To better understand in which locations worldwide the use of electric fans would be beneficial we compared the results obtained from the heat balance model with the climatic data provided in the 2017 ASHRAE Handbook–Fundamentals [33]. We also used the records from the Emergency Events Database (EM-DAT) which contains a list of the deadliest heatwaves recorded from 1936 to the present date [37].

From the ASHRAE climatic design dataset, we extracted weather data from more than 5000 stations worldwide. For each station, we collected the maximum extreme t_{db} with a 20-year return period and the t_{db} corresponding to the hottest 0.4 % of annual cumulative frequency of occurrence, and the mean coincident wet-bulb air temperature (t_{wb}). ASHRAE defines the return period as the reciprocal of the annual probability of occurrence. Hence the 20-year maximum extreme t_{db} each year has a probability of being exceeded of 5 %. For more information about this dataset please refer to Chapter 14 of the 2017 ASHRAE Handbook–Fundamentals [33]. The location of the stations and their respective maximum extreme dry-bulb temperatures are shown in Fig. 1. We do not show data from stations with a maximum temperature lower than 26 °C since we are only interested in assessing the benefit of using fans during hot days.

Few data are available for Sub-Saharan Africa where approximately 40 % of the poorest people in the world reside and where climate change may be an acute threat [38].

To determine the coincident value of RH when the maximum extreme t_{db} with a 20-year return period was recorded we first determined the humidity ratio for each location using the t_{db} corresponding to the hottest 0.4 % of annual cumulative frequency of occurrence and the mean coincident t_{wb}. We then assumed that during a heatwave the humidity ratio would remain constant while only the value of t_{db} would increase. This assumption allowed us to estimate, for each location, the value of RH for each extreme t_{db}. This is an approximation, and it does not take into account that during heat waves the value of humidity ratio may also increase.

We also assumed that during heatwaves t_{db} and RH indoors would be equal to t_{db} and RH outdoors. Conditions indoors may be less severe than outdoors since the thermal mass of buildings may dump and shift peaks in outdoor temperature. At the same time, the opposite scenario can also occur if there is a significant amount of internal load or solar gains indoors. We are aware that this assumption has some limitations, however, we deemed it to be an acceptable approximation. One possible solution was to simulate several building archetypes under different climatic conditions. However, we would still have to make assumptions such as internal loads, geometry, and building materials. This would ultimately have lead to uncertainties in the estimation of

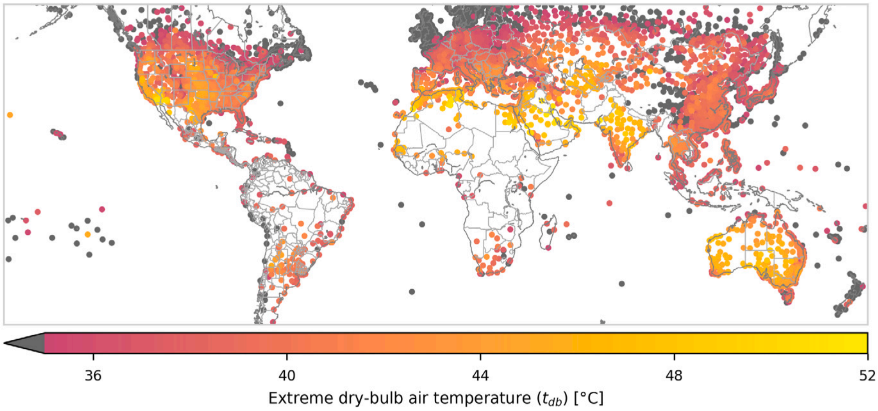


Fig. 1. Shows the location of each weather station that was included in the analysis and the maximum extreme dry-bulb temperature with a 20 year return period.

t_{db}. Moreover, we did not have access to the time series data for the past 20 years for those 5000 stations.

The EM-DAT contains detailed information on when the heatwave occurred, the location, the number of deaths, and the maximum temperature recorded. However, it does not contain information about the RH which is important for determining whether the use of electric fans would have been beneficial or not.

2.5. City population data

We obtained the city population data from the demographic statistics database which is compiled and maintained by the United Nations (UN) statistics division [39]. The database contains data up to August 2020. We used it to gather information about the number of people who live in the 115 most populous cities in the world. When available we used the population of the urban agglomerate rather than of the city administrative boundary. We then combined the population with the ASHRAE weather data to determine during extreme heat events: i) how many people were at high risk of experiencing t_{db} higher than 35 °C, and (ii) how many people would benefit from the use of electric fans. As mentioned in Section 2.4 weather data were not available for all the major cities in the world.

3. Results

3.1. Heat losses, gains, and physiological variables

The sensible heat loss from the skin to the environment is proportional to the difference between the t_{sk} and t_o, as shown in Eq. (3). Consequently, for values of t_o higher than t_{sk} the body gains sensible heat from its environment and the term $C+R$ becomes negative. Fig. 2A shows how sensible heat loss estimated with the Gagge et al. [25] and the Jay et al. [19] models vary as a function of t_o, RH, and V.

The former model iteratively determines t_{sk}, while the latter assumes it to be constant and equal to 35 °C, which is equivalent to a fully vasodilated state. When heat gains exceed heat losses, the Gagge et al. [25] model estimates that some heat energy is stored in the body and consequently t_{sk} increases, as shown in Fig. 3A and 3C, respectively. This reduces the rate at which sensible heat gain increases as t_o increases.

The values of w for two air speeds are shown in Fig. 2B. The skin wettedness is allowed by the model to increase until it reaches the value of w_{max}, after that, it plateaus and remains constant and thermal stress is expected to occur. For young adults, Jay et al. [19] assumed w_{max} to be equal to 0.65 for the 'fan on' condition and 0.85 for the 'fan off' condition. The values of w_{max} estimated by the Gagge et al. [25] for the same air speeds are lower (Fig. 2B). The operative temperature at which w equals w_{max} is inversely proportional to the value of RH. For t_o higher than t_{sk}, the negative effect that an increase in V has on sensible heat gain is compensated by a greater increase in the total rate of evaporative heat loss from skin (E_{sk}) that the body can dissipate towards the surrounding environment. For example, when t_o=45 °C and RH=30 %, a change in V from 0.2 to 4.5 m/s increases $(C+R)$ by 27.3 W/m^2 while increasing E_{sk} by 42.7 W/m^2, which provides a net positive effect.

Fig. 2C shows the values of E_{max} estimated by replacing w in Eq. (7) with w_{max}. The value of E_{max} decreases as t_o increases since p_a grows more rapidly than $p_{sk,s}$. For a set combination of V and t_o the value of E_{max} decreases as the value of RH increases because humid air has a higher p_a than dry air. The reduction in E_{max} estimated by Gagge et al. [25] model is lower than the one estimated by Jay et al. [19] since an increase in t_{sk} elevates the vapor pressure gradient between the skin and its surrounding environment.

The rate at which regulatory sweat is generated (m_{rsw}) is shown in Fig. 2D. The difference between the results obtained with the two heat balance models can be attributed to the fact that Jay et al. calculate the value of m_{rsw} as a function of the required latent energy that the body should, in theory, dissipate to achieve thermal neutrality and the required evaporative efficiency of sweating (i.e., the amount of sweat produced that evaporates). The latter was estimated using ISO 7933 equation, and it is estimated as a function of w alone. On the other hand, Gagge et al. calculate the value of m_{rsw} as a function of regulatory signals and they assume that m_{rsw} cannot exceed 500 mL/h. The excess heat stored in the human body (S_{cr} + S_{sk}), t_{sk}, and t_{cr} are shown in Fig. 3A, 3C, and 3D, respectively. When the body can no longer dissipate exogenous and endogenous heat gains, the excess heat causes t_{sk} and t_{cr} to rise.

3.2. Heat stress

The combination of t_o, RH, and V at which heat stress is predicted to occur is presented in Fig. 4(a). Each line demarcates the conditions above which not all adult healthy individuals would be able to compensate for endogenous and exogenous heat gains and therefore, if possible, they should avoid being exposed to these conditions. The Figure shows the results obtained with both the Gagge et al. [25] and the Jay et al. [19] models. For a specific value of V, the maximum t_o at which heat strain is estimated to occur decreases as the value of RH increases since, as previously shown, the value of E_{max} is inversely proportional to RH. In addition, for a specific value of RH, as the value of V grows, the overall increase in the maximum critical temperature rapidly decreases, this is not shown in the Figure. For example, in an environment with RH=60 %, increasing V from 0.2 m/s to 0.8 m/s and then to 4.5 m/s leads to an increase of the critical temperature of approximately 1.6 °C and 0.6 °C, respectively. The slope of the heat stress curve flattens at low values of RH. The RH value at which the curve flattens is proportional to V. This can be explained by the fact

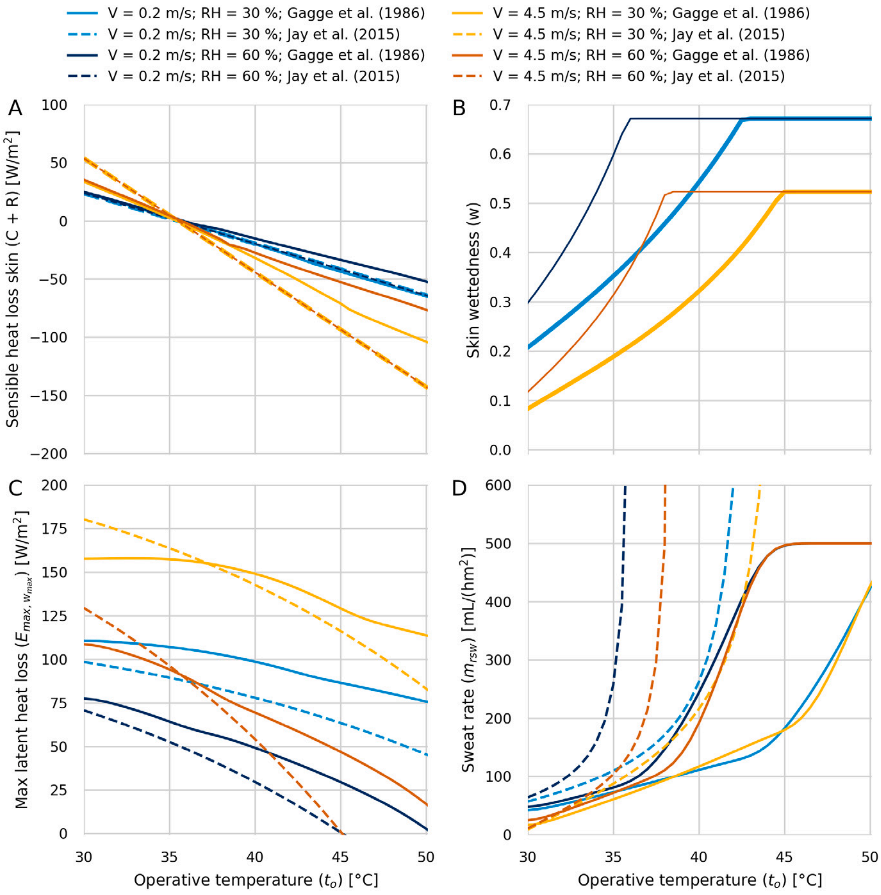


Fig. 2. Results obtained with the energy models proposed by Jay et al. [19] and Gagge et al. [25]. Each Figure shows how a variable changes as a function of t_o for a set combination of RH and V. Figure: A) sensible heat loss from skin ($C + R$). B) skin wettedness (w). C) maximum rate of evaporative heat loss from skin (E_{max}) estimated using $w = w_{max}$. D) rate at which regulatory sweat is generated (m_{rsw}).

(not shown in the Figures) that for low values of RH skin blood flow reaches its upper limit causing thermal strain. As previously stated in Section 2.2, for temperatures higher than the one at which the two heat strain curves intersects electric fans should not be used. In the region where the heat stress curve for elevated air speeds is lower than the one for ‘still air’ electric fans can only be used if the hot and dry air is pre-cooled to a point below the ‘elevated air speed’ heat stress line. This can be achieved using passive cooling strategies such as evaporative cooling. Jay et al. [19] model fails to account for this aspect and overestimates the benefits of using fans for RH values lower than 20 % and t_{db} above 46 °C, please refer to Section 3.4 for more information.

3.3. Metabolic rate and clothing

To better understand how personal factors would impact the body’s ability to dissipate heat, we calculated when heat stress would occur for different combinations of M and I_{cl}. Results for people wearing light summer clothing (walking shorts, short-sleeve shirt and sandals, I_{cl}=0.36 clo), and office summer clothing (trousers, short-sleeve shirt, and closed shoes I_{cl}=0.5 clo) who are either seated reading or writing (M=1.0 met) or standing relaxed (M=1.2 met) are shown in Fig. 4(b).

As expected, decreasing both M and I_{cl} has a net positive effect since it reduces both heat gain and thermal resistance, respectively. For values of RH below 20 % the model predicts that heat strain will be delayed by slightly increasing clothing levels. In these conditions people can easily sweat despite the higher clo level and additional clothing will reduce sensible heat gains. It should, however, be noted that these results are affected by i_{cl}, hence, we allow `pythermalcomfort` users to change the value of i_{cl}.

3.4. Humidity-dependent temperature thresholds for fan usage

The environmental conditions above which the use of elevated air speeds would be detrimental according to Gagge et al. [25] for V=4.0 m/s are shown in Fig. 5.

We use a red shading to highlight the region in which electric fans should not be used, while we use a green background to depict when elevated air speed can be used to cool the human body. We also plotted the lines above which thermal stress is expected to occur (see Fig. 4(a) for more details). Electric fans should not be used, for t_{db} higher than the one at which the heat stress curve for elevated air speeds intersect the one for ‘still air’ conditions. In the dark green area, while the use of fans is still beneficial, not all adult healthy individuals would be able to compensate for endogenous and exogenous heat gains and may experience heat strain.

We also compared Gagge et al. [25] model results with those from laboratory-based physiological studies. In Fig. 5 we present the results obtained by Morris et al. [22] and Ravanelli et al. [18]. The former determined that electric fans (V=2.0 m/s) are beneficial when t_{db}=40 °C and RH=51 %, but should not be used when t_{db}=47 °C and RH=15 %. Ravanelli et al. [18] concluded that electric fans (V=4.0 m/s) help in preventing heat-related elevation in heart rate and t_{cr} in both of the following conditions t_{db}=42 °C and RH=50 %, and t_{db}=36 °C and RH=80 %. Results obtained with the Gagge et al. [25] model are in agreement with those obtained by both field experiments.

As previously mentioned, the enthalpy of the air in Morris et al. [22] experiment was lower in the scenario with higher temperature and lower RH. The black dashed lines, in Fig. 5, are isoenthalpic lines passing through the conditions studied by Morris et al. [22]. As shown in Fig. 5 the enthalpy of hot and dry air (RH<35 %) is equal or lower

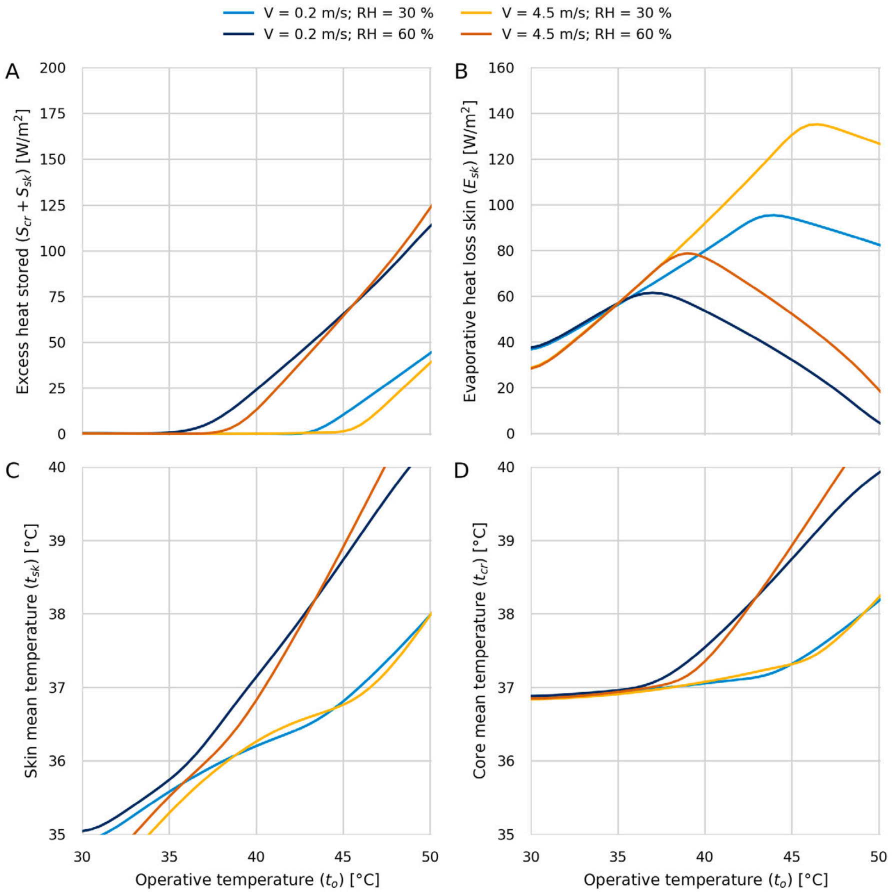
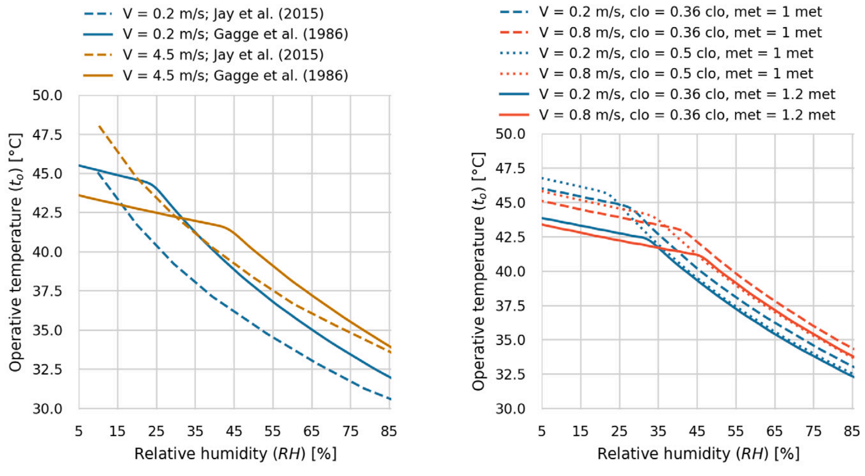


Fig. 3. Results obtained with Gagge et al. [25] energy model. Each Figure shows how a variable changes as a function of t_o for a set combination of RH and V. Figure: A) Excess heat stored in the human body, skin and core compartments (S_{sk} + S_{cr}). B) total rate of evaporative heat loss from skin (E_{sk}). C) skin mean temperature (t_{sk}). D) core mean temperature (t_{cr}).



(a) Predicted limits above which thermal strain is estimated to occur. The figure shows the results calculated using the Gagge et al. (1971) model and the Jay et al. (2015) models. Each line demarcates the point above which heat strain is expected to occur.

(b) Each line demarcates how different combinations of personal factors (e.g., M, I_{cl}) and environmental factors affect the point above which the body can no longer dissipate all the endogenous and exogenous heat gains.

Fig. 4. Heat strain limits.

than the enthalpy of the air in the green region. Consequently, evaporative cooling can be used to first reduce t_{db} to a value within the green region, and subsequently electric fans can be safely used. Evaporative cooling can be achieved by spraying water in the air or even by placing wet towels near the electric fan. Other cooling strategies, such as active cooling, can also be used to cool the air. However, we are emphasizing the importance of using evaporative cooling since we are assuming that people who mostly rely on electric fans for cooling may not have access to compressor-based air conditioning.

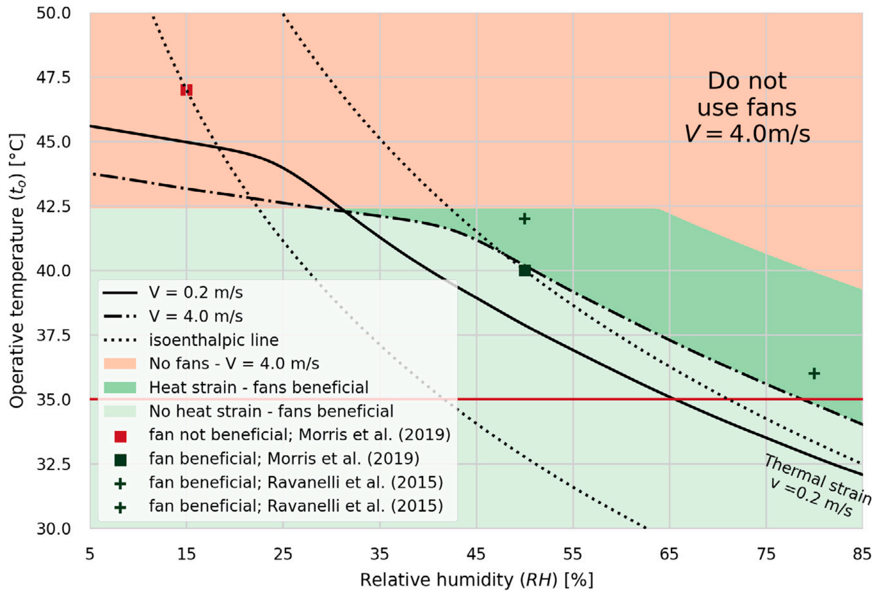


Fig. 5. The green areas show the environmental conditions in which the use of fans (V=4.0 m/s) is beneficial since they provide additional cooling to the human body. In the dark green region, while the use of fans is still beneficial, people are most likely to suffer from heat strain. The red area demarcates the region in which electric fans should not be used. The dotted lines show the isoenthalpic lines passing through the conditions studied by Morris et al. [22]. We plotted these lines to show that some points in the 'do not use fans' region have a lower enthalpy than points in the green area. Consequently, passive cooling strategies, such as evaporative cooling, may be used to reduce t_{db} to a value within the green region. The red solid line shows the max temperature at which fans should be used based on WHO and Ready.gov guidelines [1,15]. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Finally, Fig. 6 compares the results obtained using the Gagge et al. [25] with those obtained using the PHS [29]. Results were obtained by comparing the 'still air condition' with V=0.8 m/s, and the predictions of both models overall are similar. The PHS model fails to predict that fans should not be used in dry climates when the t_{db} exceeds 43.5 °C. On the other hand PHS results are more conservative for high values of RH, with the PHS model discouraging the use of elevated air speeds for t_{db}=37.5 °C and RH=85 %. It should be noted that these latter conditions are extremely rare worldwide.

3.5. Benefits of using electric fans

To understand in which locations worldwide the use of electric fans would be beneficial, in Fig. 7 we overlaid a plot showing the environmental conditions under which fans can be used with a scatter plot depicting the maximum extreme weather conditions recorded worldwide in more than 5,000 stations.

We determined that in approximately 90.0 % of the locations the use of electric fans that can generate V up to 0.8 m/s would be beneficial. In the remaining locations electric fans should not be used unless any form of cooling (including evaporative cooling) is used to pre-cool the air to any point in the green region.

To better quantify how many people would benefit from the use of electric fans we combined the city with the weather data. The former contained data from the 115 most populous cities worldwide. We plotted the data in Fig. A.9 in Appendix.

Each marker shows where the city is located, the dot size is proportional to the number of people living in that urban area, while the color shows the extreme t_{db} recorded in that city. In 2020, a total of approximately 650 million people (8 % percent of the global population) lived in the urban agglomerate of the 115 largest cities. In 95 of these cities, t_{db} higher than 35 °C were recorded and their total population was approximately 550 million people.

The model predicts that 529.0 million inhabitants, living in 93 of the most populous cities, would be better off using electric fans (V up to 0.8 m/s) rather than not using them and they should not experience heat strain. We plotted the results in Fig. A.10 in Appendix. The Gagge et al. [25] model predicted that healthy adults living in 94 cities (approximately 520.9 million inhabitants) should not experience heat strain even without increasing air movement. However, they should still be encouraged in using electric fans to improve their thermal conditions in an energy-efficient way.

We also compared these data with the records available in the Emergency Events Database (EM-DAT) [37]. A total of 122 heatwave events in the EM-DAT had information on the maximum air temperature recorded. These heatwaves were the cause of approximately 117,000 deaths, out of which a total of 102,876 and 3,803 people died during heatwaves with maximum temperatures lower than 45 °C and 40 °C, respectively. During heatwaves as t_{db} increases RH generally decreases, hence, it may be hypothesized that the use of electric fans would have been beneficial in most of those scenarios.

3.6. Sweat rate

The predicted values of m_{rsw} for V=0.2 m/s at different combinations of t_{db} and RH are shown in Fig. 8A while the predicted differences in m_{rsw} between V=0.8 m/s and V=0.2 m/s are shown in Fig. 8B. In most of the combinations of t_{db} and RH the predicted values of m_{rsw} are slightly higher in the 'still air conditions' than when V=0.8 m/s. On the other hand, m_{rsw} are higher with fan use when RH is lower than 40 % and t_{db} higher than 40 °C. This can be explained by the fact that with low RH and high t_{db} almost all the sweat secreted on the skin surface would evaporate even without a fan, due to the high gradient in water vapor pressure between the skin and the air. With elevated air speeds, more sweat is needed to compensate for the additional sensible heat gains. It should be noted, that in these conditions the maximum predicted difference in sweat losses due to fan use is always lower than 30mL/h, a difference that could be compensated by the ingestion of approximately 1 glass (250mL) of water every 8 h.

4. Discussion

We used a heat balance model developed by Gagge et al. [25] to determine under which environmental and personal conditions the use of electric fans for cooling becomes detrimental for healthy adults. We compared our results with those obtained from other physiological

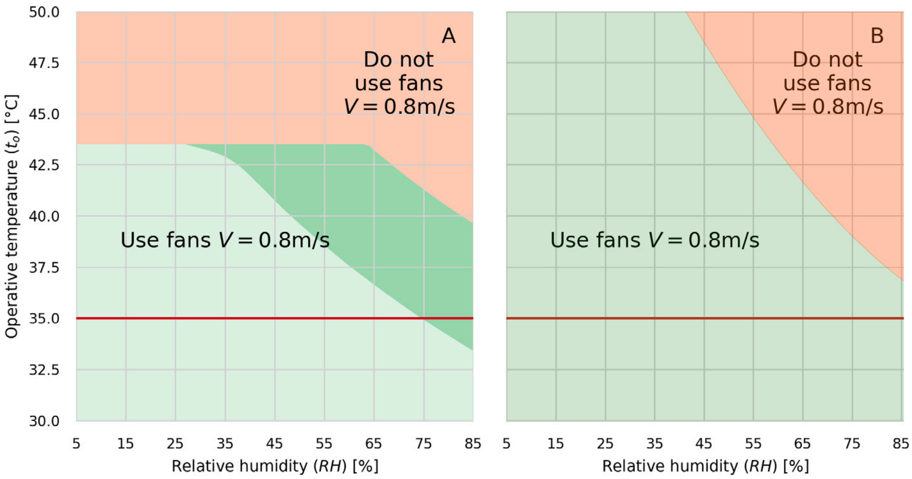


Fig. 6. Comparison results obtained with Gagge et al. [25] (A) and PHS models (B) for V=0.8 m/s. For more information on how to interpret the Figure please refer to the caption of Fig. 5. In the dark green region, the Gagge et al. [25] model estimates that while the use of fans is still beneficial, people are most likely to suffer from heat strain.

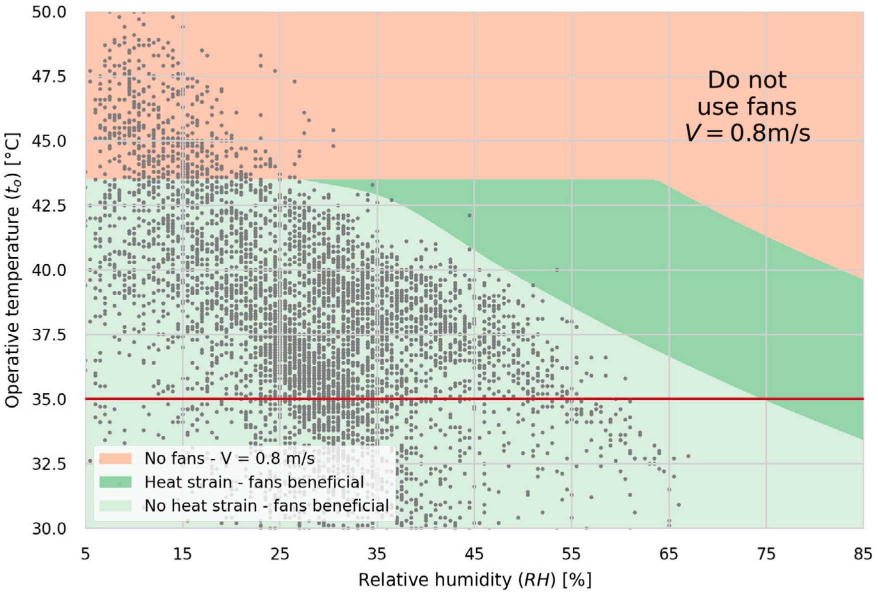


Fig. 7. Environmental conditions under which the use of electric fans is beneficial, for more information on how to interpret the Figure please refer to the caption of Fig. 5. The dots show the maximum extreme climate conditions recorded over the last 20 years in more than 5000 locations worldwide.

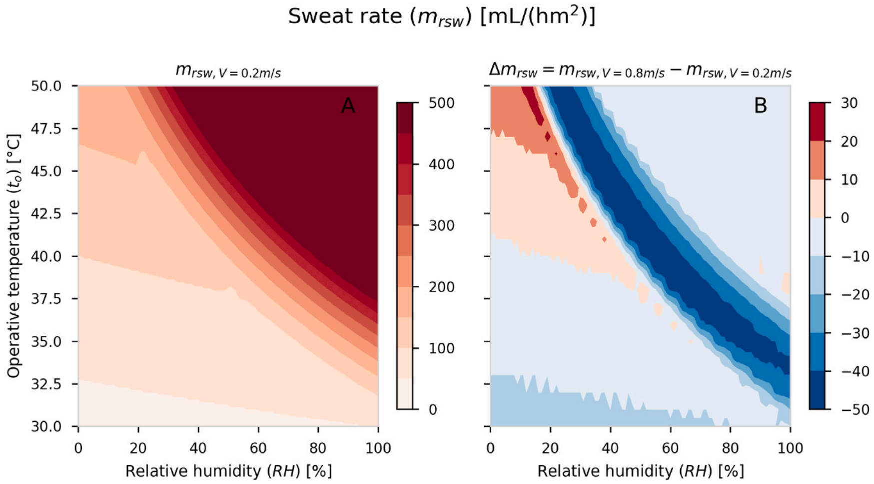


Fig. 8. Predicted rate at which regulatory sweat is generated (m_{rsw}) at different combinations of dry-bulb air temperature (t_{db}) and relative humidity (RH) for two values average air speed (V)=0.2 m/s and 0.8 m/s.

models [19,29] and empirical results from laboratory-based physiological studies [18,22]. Our results show that public health guidelines that discourage fan usage when t_{db} exceeds 35 °C are too conservative. This can be explained by the fact that while sensible heat gain increases as t_{db} exceeds t_{sk}, this is more than offset by the increase in latent heat loss under conditions that do not permit complete evaporation without elevated air speed. Consequently, the use of fans at t_{db} higher than 35 °C could yield substantial benefits for young healthy adults free of sweating impairments. This is true for approximately 90.0 % of recorded extreme heat events worldwide. For example, at RH=60 % increasing the average air speed from 0.2 m/s to 0.8 m/s raises the temperature threshold above which heat strain would occur by 1.6 °C.

This is supported by empirical evidence from a laboratory study, comprising 12 healthy men, that showed that for t_{db}=47 °C and RH=15 % fan use is not advisable. In these conditions, fan use accelerates the development of hyperthermia since sweat can easily evaporate even without elevated air movement, but they increase convective heat gain [8]. We determined that for t_{db} above 43.5 °C elevating air speed beyond 0.8 m/s would be detrimental. This threshold temperature is inversely proportional to the value of V, and it decreases to 42.4 °C if an air speed of 4.0 m/s is used to cool the human body. Both the Jay et al. [19] and the PHS [29] models fail to account for this. As previously noted in Section 2.1, the estimation of sensible heat gains using the Jay et al. [19] is more conservative since they assume t_{sk} to be constant. This explains why for RH values higher than 25 % Gagge et al. [25] model predicts that thermal strain occurs at higher t_{db} than Jay et al. [19] model as detailed in Section 3.2. We obtained similar results when comparing Gagge et al. [25] and PHS models. Their results slightly differ in very hot and humid conditions with the latter model discouraging the use of fans for t_{db}=37.5 °C and RH=85 %. However, as shown in Fig. 7 these conditions are extremely rare worldwide. Consequently, we concluded that the Gagge et al. [25] model is more appropriate in estimating humidity-dependent temperature thresholds at which electric fans would become detrimental compared with previously proposed models. In addition, the Gagge et al. [25] model was previously tested for its relevance under realistic airflow and air velocities produced by ceiling and desk fans, such as partial immersion in the elevated flow, and flows with different turbulence intensity [28]. At the time of writing this manuscript Morris et al. [8] published an article in which they improved on the Jay et al. [19] model. Despite the fact that Morris et al. [8] used slightly different equations they obtained similar conclusions to those we are presenting here. However, we believe that readers will benefit from reading our manuscript since we generated our results using a 'more realistic' value for V (0.8 m/s instead of 3.5 m/s); have released a web-based tool that allows users to determine how environmental and personal factors affect the humidity-dependent temperature thresholds; and, have published our source code on a public repository. Moreover, corroboration is a key aspect in research. We only used a value of V=4.0 m/s to compare the results of the Gagge et al. [25] model with those previously obtained by Jay et al. [19] and Morris et al. [8]. However, results obtained with V=4.0 m/s may be difficult to generalize since such high air speeds cannot be easily achieved by most electric fans [9,24] available on the market, and the airflow may not be equally distributed around the entire body. Nevertheless, we do not have yet a detailed map that relates the airspeed around the human body for different types of fans, hence more research is needed [24]. The Gagge et al. [25] model assumes that in non-uniform environments V is equal to the average air speed measured at 0.1, 0.6, and 1.1 m height for seated occupants and at 0.1, 1.1, and 1.7 m for standing occupants. These air speed values must be obtained experimentally and a standard method of test should be developed for all type of fan, similarly to what was done for ceiling fans [40].

Electric fans are a cheaper and more energy-efficient alternative to compressor-based air conditioning. Fans require less energy to operate, have lower operational and maintenance costs, and do not use refrigerants that potentially harm the environment. If battery-operated, they can also be used during power outages. This is significant because using compressor-based cooling to avoid heat stress is both environmentally and economically disadvantageous. In 2017, approximately 43.6 % of the world population lived on less than $5.50 per day, respectively [38]. People that cannot afford air conditioning due to limited financial means, and have limited access to electricity, should certainly not be discouraged from using fans when t_{db} exceeds t_{sk}. Similarly, even in upper-middle and high-income countries, where access to electricity is less of a concern, low-income people are among those who are most at risk during heatwaves and may not be able to cool or leave their homes. Hence, healthy adults should not be discouraged from using electric fans when either outdoor or indoor temperatures exceed 35 °C. Elevating air speed indoors has the additional benefit of reducing peak energy demand and the burden on the electric grid while reducing global greenhouse gas emissions. While extra sweat losses caused by fans in dry and hot conditions can be compensated with the ingestion of water.

To help people worldwide to determine under which environmental and personal conditions the use of fans becomes detrimental we developed a free, open-source, and easy-to-use online tool. The tool can be accessed by any device that has a web browser at this URL: https://comfort.cbe.berkeley.edu. In addition, we also included the source code we used in this manuscript in `pythermalcomfort` so anyone can reproduce our results. These tools allow users to perform complex calculations and visualize the data without the need to re-writing the programming code.

Limitations

The Gagge et al. [25] heat balance model uses coefficients that were estimated empirically, and some simplified equations (e.g., to calculate the respiratory losses). Results obtained with Gagge et al. [25] model are estimations for standard subjects in good health and fit. The model does not predict the physiological response of a single individual subject, and the recommendations provided in this manuscript are not intended to substitute professional medical advice. Consequently, results may not apply to all individuals, such as those who demonstrate sweating impairments due to factors such as age, anticholinergic medications, or other pre-existing conditions that interfere with thermoregulation. More empirical evidence is needed to validate the applicability of this model under different environmental conditions and to more vulnerable people for example the elderly. In particular, more evidence is needed to estimate the applicability of the Gagge et al. [25] model in hot and dry conditions, i.e., RH lower than 20 % and t_{db} higher than 40 °C. Since hyperthermia is not the only cause of death during extreme weather events, hot and dry environments can exacerbate cardiovascular strain due to rising skin blood flow [8]. While the Gagge et al. [25] accounts for this more laboratory-based research is needed to ensure that fan use does not exacerbate cardiovascular strain in healthy adults in the above-mentioned conditions.

5. Conclusions

Several health guidelines regarding electric fan use during heatwaves appear to underestimate the benefit that air movement has in cooling people when dry-bulb air temperature (t_{db}) exceeds skin mean temperature (t_{sk}).

We used a heat balance model to estimate heat losses and physiological variables as a function of environmental and personal factors [26]. We were able to determine under which combination of environmental and personal parameters electric fans can be safely and effectively used to cool healthy adults.

Our results show that electric fans are a safe solution to cool people even when t_{db} exceeds t_{sk}. For values of RH higher than 22 % air speed of 0.8 m/s increases the critical air temperature at which both an elevated cardiovascular and thermal strain occurs by an average of 1.4 °C. Moreover, even above these critical temperatures, electric fans are still not harmful and may provide marginal benefits to people, as shown in Fig. 5. In very hot environments with t_{db} exceeding 43.5 °C fans (average air speed (V)=0.8 m/s) should not be used since air movement may increase the risk of cardiovascular strain. It should be noted that this threshold temperature is inversely proportional to the value of V surrounding the occupant. In these extreme conditions, which are relatively rare and occur only in a few locations worldwide, electric fans can only be used after other cooling technologies (including evaporative cooling) are used to reduce the temperature below 43.5 °C for V=0.8 m/s.

We conclude that the public should therefore not be advised to stop using electric fans during heatwaves when temperatures outdoors or indoors are higher than 35 °C. As heatwaves are becoming more frequent and intense due to climate change, public health recommendations regarding the use of electric fans should be reviewed to help minimize heatwave-related morbidity and mortality.

To help policymakers and people worldwide we incorporated the model into an open-source, free-to-use web-based online tool. Our tool allows users to determine when people can safely use elevated air speeds to cool themselves by providing interactive result visualizations. The link to our online tool is: https://comfort.cbe.berkeley.edu. We included the source code we used in the Python package `pythermalcomfort`.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix. Population and weather data

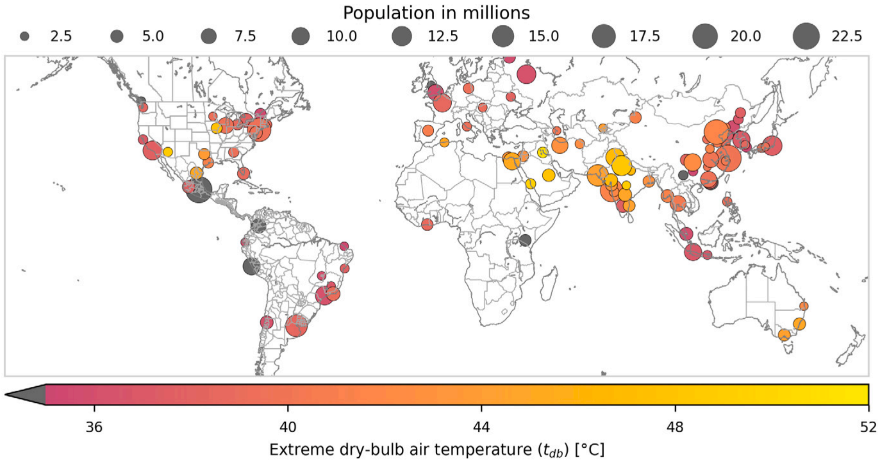

Fig. A.9. Most populous 115 cities worldwide.

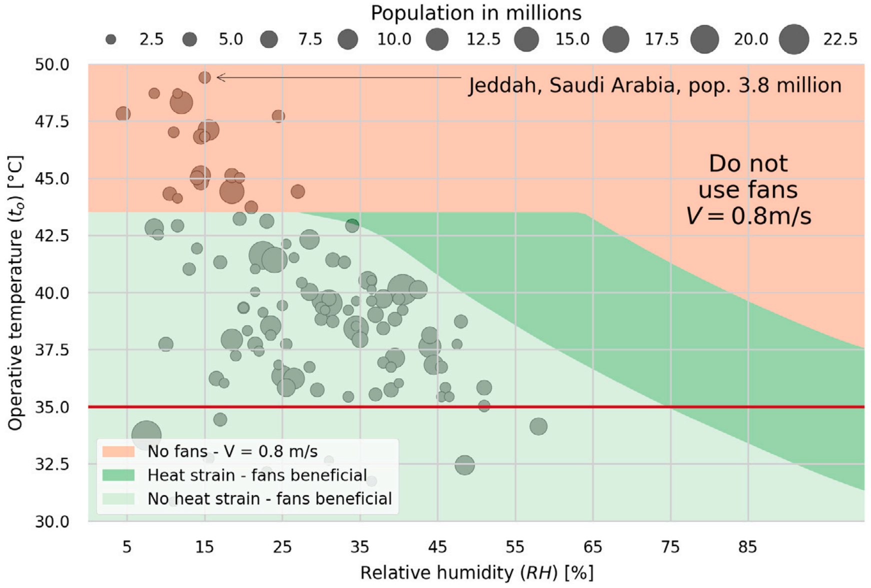

Fig. A.10. Environmental conditions under which the use of electric fans is beneficial, for more information on how to interpret the Figure please refer to the caption of Fig. 5. Each dot shows the maximum extreme climate conditions recorded over the last 20 years in each of the 115 most populous cities worldwide.

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