# Energy balance model to determine benefits of using electric fans during heatwaves

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**Abstract**

The WHO classifies heatwaves as one of the most dangerous natural hazards and it estimates that from 1998–2017 more than 166'000 people died worldwide. Heatwaves mostly affect specific socioeconomic (e.g., poor) and demographics groups (e.g., elderly), those who work outdoors, and those with pre-existing conditions. Electric fans are an effective, efficient and economical solution to cool the human body. Fans are one of the cheapest cooling technology available on the market. However, many national and international guidelines discourage people from using them when indoor air temperatures exceed 35 °C. To verify the validity of those recommendations, we used an heat balance model to determine under which environmental (e.g., air temperature, air speed) and personal (i.e., metabolic rate, clothing) conditions the use of fans would be beneficial for cooling people. Our results show that most of the current national and international guidelines underestimate the beneficial effect of elevating air speed in extreme temperature events. Electrical fan can safely be used in a wide range of conditions even if the indoor dry-bulb temperature exceeds the skin temperature. The use of elevated air speeds would on average increase by 2.0 °C the critical temperature at which heat strain is expected to occur. It should also be noted that the maximum operative temperature at which the use

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of elevated air speeds becomes detrimental is inversely proportional to the relative humidity. To better help users understanding under which environmental and personal conditions electrical fans can effectively cool the human body, we also developed a free, easy-to-use web-based tool.

*Keywords:* Air movement, Extreme temperature events, Energy conservation, Hydration, Heat stress

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**Nomenclature**

| | |
|---|---|
| $t_{db}$ | dry-bulb air temperature, °C |
| $t_o$ | operative air temperature, °C |
| $t_{cl}$ | clothing temperature, °C |
| $RH$ | relative humidity, % |
| $V$ | average air speed, m/s |
| $\overline{t_r}$ | mean radiant temperature, °C |
| $I_{cl}$ | total clothing insulation, clo |
| $M$ | rate of metabolic heat production, W/m$^2$ |
| $t_{sk}$ | skin mean temperature, °C |
| $t_{cr}$ | core mean temperature, °C |
| $R_{cl}$ | thermal resistance of clothing, m$^2$K/W |
| $R_{cl}$ | evaporative heat transfer resistance of clothing layer, m$^2$kPa/W |
| $f_{cl}$ | 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) |
| $h_r$ | linear radiative heat transfer coefficient, W/(m$^2$K) |
| $h_c$ | convective heat transfer coefficient, W/(m$^2$K) |
| $h_e$ | evaporative heat transfer coefficient, W/(m$^2$kPa) |
| $A_{body}$ | body surface area, m$^2$ |
| $mass$ | body mass, kg |
| $height$ | body height, m |
| **SET** | Standard Effective Temperature, °C |
| $S_{cr}$ | rate of heat storage in the core compartment, W/m$^2$ |
| $S_{sk}$ | rate of heat storage in the skin compartment, W/m$^2$ |
| $E_{res}$ | rate of evaporative heat loss from respiration, W/m$^2$ |
| $E_{dif}$ | rate of evaporative heat loss from moisture diffused through the skin, 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$^2$ |
| $E_{max}$ | maximum rate of evaporative heat loss from skin, W/m$^2$ |
| $C_{res}$ | rate of convective heat loss from respiration, W/m$^2$ |
| $C+R$ | sensible heat loss from skin, W/m$^2$ |
| $q_{res}$ | total rate of heat loss through respiration, W/m$^2$ |
| $q_{sk}$ | total rate of heat loss from skin, W/m$^2$ |
| $w$ | skin wettedness |
| $w_{max}$ | skin wettedness practical upper limit |
| $m_{rsw}$ | rate at which regulatory sweat is generated |
| $p_{sk,s}$ | water vapor pressure at skin, kPa |
| $p_a$ | water vapor pressure in ambient air, kPa |
| **WMO** | World Meteorological Organization |
| **WHO** | World Health Organization |
| **EPA** | United States Environmental Protection Agency |

## 1. Introduction

Anthropogenic activities are the primary causes of global warming. From the pre-industrial period human activities are estimated to be the primary cause of a 1 °C increase in the Earth's global average temperature [1]. Since 1981 the combined land and ocean temperature has increased at an average rate of 0.18 °C per decade [2]. As a consequence, nine of the ten warmest years on records have occurred since 2005 [3]. It is estimated that by 2030 the rate at which the global average temperature increases is going to accelerate due to the heating imbalance between the greenhouse gases and the oceans' thermal inertia [3]. Consequently, due to global warming, associated risk to rising temperatures such as heatwaves are expected to increase in length, intensity and frequency [4].

While there is not an universally definition of heatwave both the World Meteorological Organization (WMO) and World Health Organization (WHO) describe them as: "a 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" [5]. Some thermoregulatory factors, demographics and socioeconomic characteristics, such as age (very young and elderly), pre-existing conditions, low income, prolonged outdoor activities, and social isolation all play a negative role and increase the heat risk of an individual during heat waves [5]. Heatwaves also put an additional burden on the health, emergency, energy, water and transportation sectors. For example, during heat waves peak demand consumption increases due to an increase energy demand for cooling, while the efficiency of the grid and the power plant decreases. This may result in power shortages and blackouts.

Both humid and dry heat conditions can affect the heat balance of the human body. Rapid changes in heat gains can compromise the ability of the body to regulate its core temperature and can worsen health of those with pre-existing conditions or result in illnesses which may even be life threatening [5]. The WHO, and the WMO together with national government agencies provide public health guidance for people to minimise heat stress during heatwaves. For example, they suggest to keep the body hydrated, to keep out of the heat and keep the home cool. However, the WHO, and several U.S.A. government agencies do not recommend the use of electric fan when temperatures exceed 35 °C [6, 7, 8, 5], despite the fact that previous research has shown that the use of electrical fans is beneficial even if the dry-bulb air temperature ($t_{db}$) is higher than the skin mean temperature ($t_{sk}$) [9, 10, 11, 9]. For example, the United States Environmental Protection Agency (EPA) Excessive Heat Events Guidebook discourages the use of electrical fans during heat waves to cool people, but instead it recommends their use to bring cooler air from outside [12]. While the latter in principle it is a good advice, natural ventilation is beneficial only when the enthalpy of air outdoors than indoors air [13]. During heatwaves people may not be fully aware of the weather conditions outdoors and heatwaves may keep their windows open during the hottest hours of the day which in turn would lead to heat gains into the building [14]. One laboratory study conducted on 12 healthy men concluded that in hot ($t_{db}$ = 47 °C) and dry conditions (relative humidity ($RH$) = 15 %) fan use is not advisable while in hot ($t_{db}$ = 40 °C) and humid conditions ($RH$ = 51 %) fans reduced core temperature and cardiovascular strain and improved thermal comfort [15]. It should, however, be noted that in the latter condition the enthalpy of the air was higher (101.0 kJ/kg) than in the former condition (73.0 kJ/kg). In the hot and dry condition heat strain arguably occurs since all the sweat can easily evaporate even without the use of elevated air movement. Consequently, in hot and dry conditions skin wetting or evaporative cooling technologies can be used to either increase latent heat loss from the skin or to slightly reduce $t_{db}$ and consequently reducing the sensible heat gains, respectively. In the latter case the use of elevated air speed can then be used to increase the evaporate heat transfer coefficient. Either of the above mentioned strategies would reduce the heat strain on the human body. For example, evaporative cooling could have been used to cool the air in the hot and dry scenario presented above ($t_{db}$ = 47 °C, $RH$ = 15 %) to the following condition $t_{db}$ = 40 °C, $RH$ = 28 %. In the latter condition the heat strain on occupants would be even lower than the condition tested in Morris et al. (2019) experiment and consequently participants would not have experienced heat strain.

Based on the available scientific evidence, advising people not to use fans when temperatures exceed 35 °C could, therefore, be detrimental for many people around the world since many of them may neither have the resources to cool their space using air conditioning, nor the ability to travel to public spaces which are cooler. Some of these people could be the elderly, people with mobility issues or poor people living either in remote areas or in developing parts of the world. These groups are already more at risk than the rest of the population, and discouraging them from utilizing electrical fans when temperatures exceed 35 °C can exacerbate heat stress. Jay et al. (2015) demonstrated that the use of fans is beneficial even if $t_{db}$ is higher than $t_{sk}$, as long as the increase in total rate of evaporative heat loss from skin ($E_{sk}$) can compensate for the extra sensible heat gains [10].

Electrical fans are relative inexpensive to buy (can be purchased for 20 USD), energy efficient, do not have any installation cost and can consume as low as few Watts of power to operate. Electrical fans can, therefore, be used as an alternative cooling technology or in combination with compressor-based air conditioning [11, 16]. Previous research has also shown that they can even be used in tropical hot and humid climates to increase occupants satisfaction with their thermal environment [17]. Therefore, elevating air speed indoors has also the potential of reducing the peak energy demand during hot days and the burden on the electrical grid.

To better understand under which environmental conditions (i.e., $t_{db}$, $RH$) the use of fans would be beneficial, Jay et al. (2015) developed a simplified heat balance model. However, their model had the following limitations, it does not: consider radial asymmetry, estimates iteratively $t_{sk}$ and core mean temperature ($t_{cr}$), allow user to change the value of rate of metabolic heat production ($M$) or total clothing insulation ($I_{cl}$). Moreover, their results are based on a single air speed velocity 4.5 m/s which cannot be achieved by most of ceiling fans [18], and pedestal fans [16]. The value of 4.5 m/s was measured at one meter away from the fan, hence, their results are difficult to generalise. Consequently, to overcome the above mentioned limitations, we are proposing the use of the heat balance model developed by Gagge et al. (1986) to estimate heat losses and physiological variables as a function of environmental and personal factors. Gagge et al. (1986) model was originally developed to calculate the Standard Effective Temperature (SET). The Gagge et al. (1986) can, however, be used to estimate the combinations of $t_{db}$, $RH$, mean radiant temperature ($\overline{t_r}$), average air speed ($V$), $I_{cl}$, $M$ at which the use of elevated air speed would be beneficial during heatwaves. In addition, to help the overall community we developed an open-source, free to use, web-based online tool which provides interactive plots and displays the results to the user. Our tool allows users to determine when people can safely use elevated air speeds to cool their body.

## 2. Methodology

In this manuscript, we used the heat balance model that Gagge et al. (1986) developed to derive the SET to determine when the use of elevated air moment (e.g., $V > 0.2$ m/s) would be beneficial to cool the human body. The heat balance model allows us to estimate how environmental (i.e., $t_{db}$, $\overline{t_r}$, $V$, $RH$) and personal factors (i.e., $I_{cl}$, $M$) 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 $t_{cr}$. It should be noted that $t_{db}$ and $V$ are the average values measured at different heights over a period of at least three minutes. These heights are 0.1, 0.6 and 1.1 m for seated people and 0.1, 1.1 and 1.7 m for standing occupants [20].

Section 2.1 describe the main Equations used by the model to derive the results. The algorithm we used to calculate the results can be found in the Appendix. Moreover, we added it to the pythermalcomfort Python package [21] and the CBE thermal comfort tool [22]. The former can be used by Python users to calculate the results presented in this manuscript. The latter is a web-based tool that can be used to generate interactive figures which show the environmental conditions under which the use of elevated air speeds is beneficial.

### *2.1. Energy Balance*

The human body exchanges both sensible and latent heat with its surrounding environment. Sensible heat is transferred via conduction, convection and radiation ($C + R + C_{res}$). While 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 rate of heat storage in the skin compartment ($S_{sk}$), and the rate of heat storage in the core compartment ($S_{cr}$) increase and in turn the $t_{sk}$, and $t_{cr}$ rise, respectively.

The amount of sensible heat gains or losses from the human body to its environment can be expressed as a function of environmental, and personal factors. The former are $t_{db}$, $\overline{t_r}$, $V$, and $RH$. While the latter are $M$, and $I_{cl}$ [23].

The equations used to determine sensible and latent heat loss are based on fundamental heat transfer theory, while the coefficient were estimated empirically [23].

#### *2.1.1. Body Surface Area, ($A_{body}$)*

All the terms presented in Equation 1 are reported in power per unit of human body surface area ($A_{body}$). Equation 2 can be used to estimate $A_{body}$ as a function of the body mass ($mass$) and body height ($height$) of the person [24].

$$A_{body} = 0.202 m^{0.425} l^{0.725} \tag{2}$$

#### *2.1.2. Sensible Heat Loss from Skin, ($C + R$)*

Sensible heat loss from the human body mainly occur from convection and radiation from the skin to the environment. The total amount of sensible heat loss from skin ($C + R$) can be described as a function of the $t_{sk}$, operative air temperature ($t_o$), 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:

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

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

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

Where $t_o$ varies as a function of convective heat transfer coefficient ($h_c$), linear radiative heat transfer coefficient ($h_r$), $\overline{t_r}$ and $t_{db}$, and it is described by:

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

The $t_{sk}$ is calculated iteratively by the heat balance model 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 the $t_o$, $t_{sk}$, $R_{cl}$ and the resistance of the air layer.

### *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 skin wettedness ($w$), 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 ($R_{cl}$).

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

Despite the fact that Equation 7 is expressed as a function of $w$. The human body does not regulates $w$ directly but, rather, it regulates the sweat rate [23]. Skin wettedness varies as a function of the activity of the sweat glands and the environmental conditions [23]. While, theoretically $w$ can range from 0 to 1, in practice, $w$ is strongly correlated with thermal stress and warm discomfort, consequently there is a skin wettedness practical upper limit ($w_{max}$) for sustained activity for healthy and acclimatized humans [23].

We estimated the $w_{max}$ value and the rate at which regulatory sweat is generated ($m_{rsw}$) using the Gagge et al. (1986) 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 [23]:

$$q_{res} = C_{res} + E_{res} = 0.0014M(34 - t_a) + 0.0173M(5.87 - p_a) \tag{8}$$

### *2.2. Data Analysis*

The heat balance model was used to estimate the sensible and latent heat loss and physiological parameters (e.g., $m_{rsw}$, $t_{cr}$). We calculated the results for $t_o$ ranging from 28 to 55 °C at 0.5 °C intervals, $RH$ ranging from 0 to 100 % at 5 % intervals and for the discrete values of $V = 0.2$, 0.8 and 4.5 m/s. In this paper we will be referring to 'still air' condition when air velocities are below $V = 0.2$ m/s. This definition is in accordance with the ASHRAE 55–2017 Standard [20] and allowed us to compare our results with those obtained by Jay et al. (2015). We assumed $\overline{t_r}$ to be equal to $t_{db}$, $I_{cl} = 0.5$ clo, and $M = 1.0$ met, unless otherwise specified. It could be argued that some people during heatwaves may be wearing less clothes than that, hence, a value of $I_{cl}$ equal to 0.36 clo (i.e., walking shorts, short-sleeve shirt and sandals) would be more appropriate, however, we wanted to use a more conservative value. Moreover, results for different combinations of environmental and personal conditions can be generated using our online tool. We reported heat losses per unit of surface area (i.e., $E_{sk}$). Thermal stress was assumed to occur when either of the following parameters reached its maximum value $w$, skin blood flow or $m_{rsw}$. We assumed that the use of electrical 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.

### *2.3. Weather data*

The results obtained with the proposed heat balance model were compared with climatic data provided in the 2017 ASHRAE Handbook–Fundamentals [23] and the records from the Emergency Events Database (EM-DAT) which contains a list of the deadliest heatwaves recorded from 1936 to the present date [25].

From the ASHRAE climatic design dataset we extracted information regarding the maximum extreme dry-bulb and wet-bulb temperatures recorded across more than 5000 stations worldwide with a 10 year return period. For more information about the ASHRAE climate design dataset please refer to Chapter 14 of the 2017 ASHRAE Handbook–Fundamentals [23]. Location of the stations and their respective maximum extreme dry-bulb temperatures are shown in Figure 1 We did not show data from stations with a maximum temperature lower than 20 °C since we are only interested in assessing the benefit of using fans during hot days.

Figure 1 also shows that few data was available for the Sub-Saharan Africa where approximately 40 % of the poorest people in the world reside and where climate change may be an acute threat [26].

For each location we assumed that the worst condition would occur if both the maximum extreme dry-bulb and wet-bulb temperatures would have been

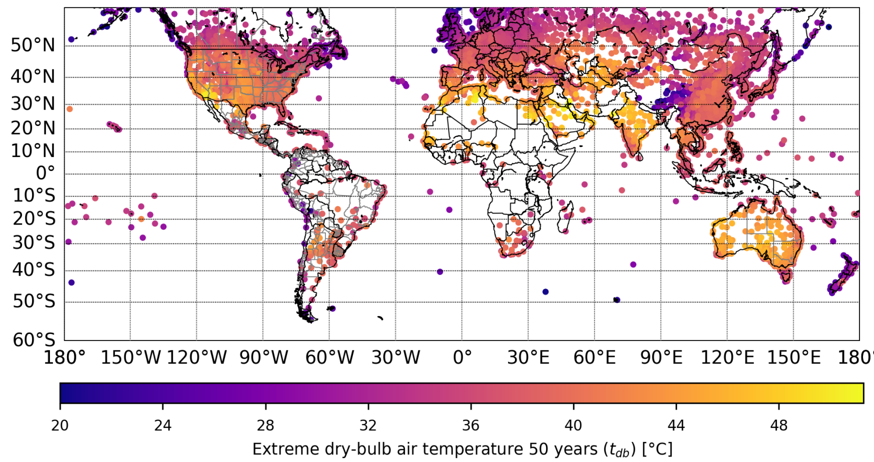


Figure 1: Shows the location of each weather station that was included in the analysis and the maximum extreme dry-bulb temperature with a 10 year return period.

recorded at the same time. This is an approximation and it is arguably overestimating the most extreme condition due to the fact that the likelihood that both conditions would occur at the same time is extremely low. However, we assumed this to be the most extreme heat event that could occur in each location. In addition, we assumed that during heatwaves $t_{db}$ and $RH$ indoors would be equal to $t_{db}$ and $RH$ outdoors. Conditions indoors may, however, be slightly less severe than outdoors since the thermal mass of the building would dump and shift peaks in outdoor temperature. On the other hand, if the house is not well shaded $\overline{t_r}$ may rise significantly and worsen conditions indoors.

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 essential in determining whether the use of electrical fans would have been beneficial or not.

### *2.4. Elderly*

### *2.5. Open-source tools*

## 3. Results

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 Equation 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. Figure 2A shows how the sensible heat loss estimated with the Gagge et al. (1986) and the Jay et al. (2015) 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. When heat gains exceed heat losses, Gagge et al. (1986) model estimates that some heat energy gets stored in the body and consequently $t_{sk}$ increases, as shown in Figure 3C. This reduces the rate at which sensible heat gain increases as $t_o$ increases.

The values of $w$ and the respective values of $w_{max}$ for two air speeds are shown in Figure 2B. The value of $w_{max}$ only varies as a function of $V$. It can be observed that the critical operative temperature at which $w$ equals $w_{max}$ is a inversely proportional to the value of $RH$.

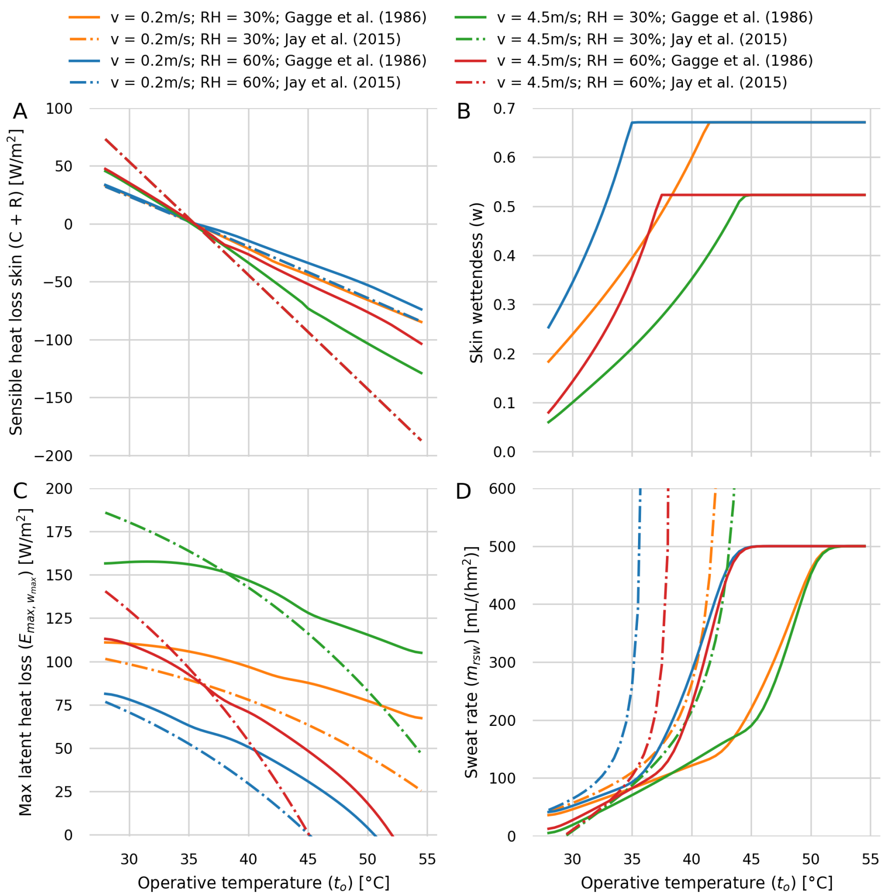


Figure 2: Results obtained with the the energy models proposed by Jay et al. (2015) and Gagge et al. (1986). Each Figure shows how each parameter varies as a function of $t_o$ for a combination of two values of $RH$ and $V$. Figure A - sensible heat loss from the skin. Figure B - skin wettendess. Figure C - Maximum latent heat loss estimated using $w = w_{max}$. Figure D - Sweat rate.

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 %, an increase in

$V$ from 0.2 to 4.5 m/s increases the sensible heat gains ($C + R$) by 29 W/m$^2$ while increasing $E_{sk}$ by 45 W/m$^2$, hence, increasing $V$ has a net positive effect.

Figure 2C shows the values of maximum rate of evaporative heat loss from skin ($E_{max}$) estimated by replacing $w$ in Equation 7 with $w_{max}$. The value of $E_{max}$ decreases as the $t_o$ 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 since humid air has a higher $p_a$ than dry air. The reduction in $E_{max}$ estimated by our model is lower than the one estimated by Jay et al. (2015) since an increase in $t_{sk}$ elevates the vapor pressure gradient between the skin and the surrounding environment.

The rate at which regulatory sweat is generated ($m_{rsw}$) is shown in Figure 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. 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 Figure 3A, 3C, and 3D, respectively. When the body cannot longer dissipate exogenous and endogenous heat gains, the excess heat gets stored in the human body causes $t_{sk}$ and $t_{cr}$ to raise.

The combination of $t_o$, $RH$, and $V$ at which heat strain would start to occur is presented in Figure 4. Each line demarcates the region in which thermal stress is estimated to occur and not all individuals would be able to compensate for endogenous and exogenous heat gains. The Figure shows the results obtained with both the Gagge et al. (1986) and the Jay et al. (2015) models. For a specific value of $V$, the maximum $t_o$ at which cardiovascular strain is estimated to occur decreases as the value of $RH$ increases. In addition, it can be observed that for a specific value of $RH$, as the value of $V$ increases the overall increase in the maximum critical temperature rapidly decreases. For example, in an environment with $RH$ = 60 %, increasing $V$ from 0.2 m/s to 0.8 m/s then to 4.5 m/s lead to an increase of the critical temperature of approximately 2.3 °C and 0.8 °C, respectively.

In addition, in Figure 4 we are presenting the results obtained by Morris et al. (2019) who studied whether the use of fans ($V$ = 2.0 m/s) is beneficial in two environmental conditions hot and humid (green dot) and hot and dry (red dot). The black dashed lines are isoenthalpic lines passing through the conditions studied by Morris et al. (2019). Our results show that if electric fans are used in hot and dry conditions heat strain would occur at relative low enthalpy values. This can be explained by the fact that the value of skin blood flow increases proportionally to the value of $V$. Our model, appears to slightly underestimate this effect since in 'theory' electrical fans should not be used for $RH$ lower than 10 % and $t_{db}$ higher than 49 °C, which is where the gray solid line intercepts the yellow line. It should, however, be noted that, as previously mentioned in the Introduction Section, the hot and dry condition has a lower enthalpy than the hot and humid one, hence, evaporative cooling technologies

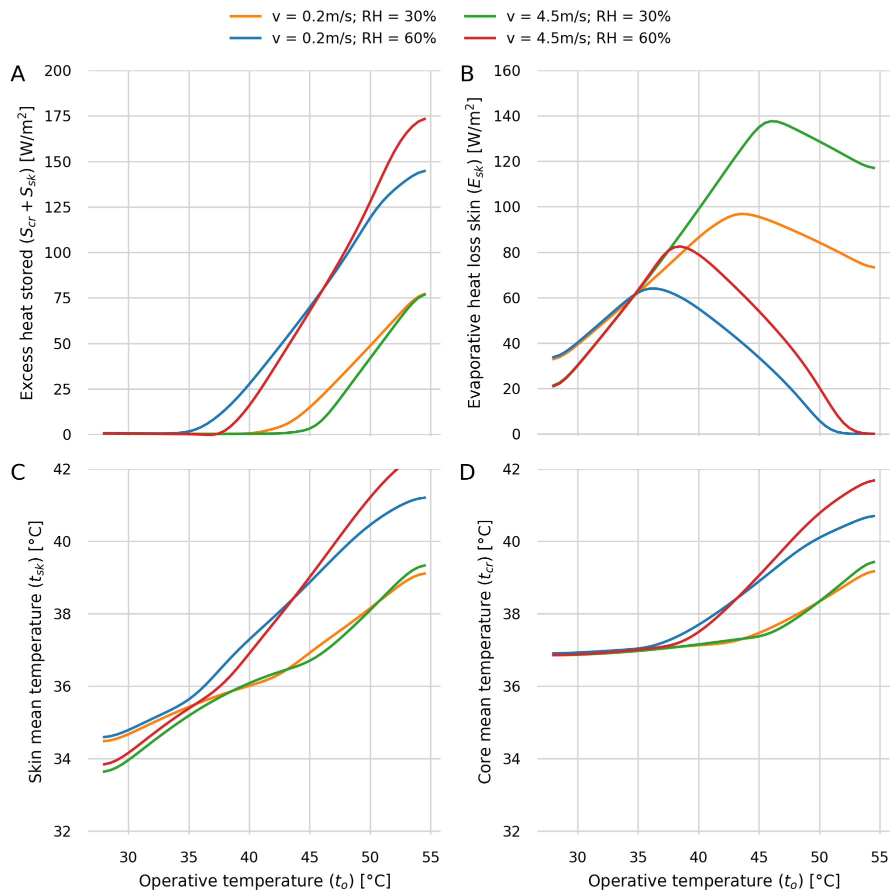


Figure 3: Caption

can be used to reduce skin blood flow and avoid heat strain. 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. Evaporative cooling can be achieved by spraying water in the air or even by placing wet towels near the electric fan.

To better understand how personal factors would impact the body ability to dissipate heat we calculate when heat strain 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 Figure 5. As expected, decreasing both $M$ and $I_{cl}$ has a net positive effect since it reduces both heat gains and thermal resistance.

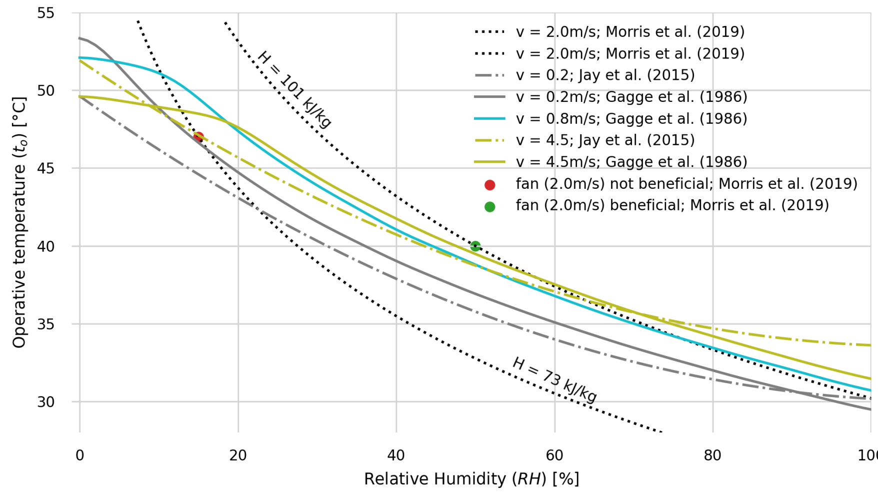


Figure 4: Compares the results between the Gagge et al. (1986) and the Jay et al. (2015) models. The solid and dash dotted lines demarcate the point above which heat stress is expected to occur. The dashed lines are isoenthalpic lines, which show the enthalpy of the two conditions studied by Morris et al. (2019)

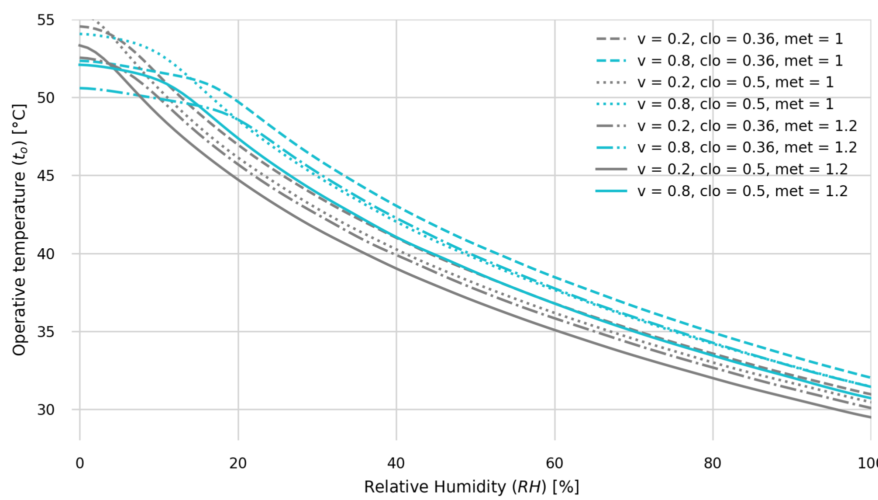


Figure 5: Each line demarcates how different combinations of personal factors (e.g., $M$, $I_{cl}$) and environmental factors affect the point above which the body cannot longer dissipate all the endogenous and exogenous heat gains

315 The environmental conditions above which the use of elevated air speeds would actually be detrimental for the great majority of people is shown in Figure 6. We used a red filling to highlight the region in which electrical fans

should not be used, while we used a green background to depict when elevated air speed can safely be used to cool the human body. We used a blue background to show the area in which fans are effective tool to prevent heat strain only if are used in combination with evaporative cooling technologies. We also plotted the lines above which thermal strain is expected to occur (see Figure 4 fro more details). For a specific value of $RH$, as the value of $V$ increases the critical temperature at which thermal strain would occur also increases, however, at the same time the temperature above which fans should not be used also decreases by a greater amount.

We used a scatter plot to visualize the maximum extreme weather conditions recorded worldwide in more than 5000 stations. Each dot represents the most extreme heat event recorded in each location. Based on the climate data obtained from the 2017 ASHRAE Handbook–Fundamentals we determined that in approximately 67 % of the locations thermal strain should not occur even without air movement, however, this number increases to 87 % and 92 % when $V$ is increased to 0.8 m/s and 4.5 m/s, respectively. The use of fans during heatwaves would, therefore, be beneficial in the great majority of the locations worldwide. With the exception of 23 locations where the use of $V$ higher than 0.8 m/s would be detrimental for the human body, and 7 locations where elevated air movement should not be used in any scenario.

## 4. Discussion

Electrical fans are a cheaper and more efficient alternative to compressor-based air condition. They consume less energy than the latter, have lower operational and maintenance cost, and do not use refrigerants who can harm the environment. However, several public health guidelines discourage their when dry-bulb air temperature ($t_{db}$) exceed 35 °C [5]. Our results show that this recommendation is inaccurate and misleading. While sensible heat gain increases as the $t_{db}$ exceeds skin mean temperature ($t_{sk}$), elevated air speeds increase by a greater amount the latent heat that the body can dissipate towards the environment. This is true for more than 99 % extreme heat events recorded worldwide. Increasing the average air speed in the space from 0.2 m/s to 0.8 m/s leads to an average increase of 1.7 (0.8, 1.4, 2.1) °C [mean, (SD, Q1, Q3)] in the temperature above which heat strain would occur. In very hot and dry conditions (i.e., $t_{db}$ = 47 °C, $RH$ = 15 %) fans should only be used in combination with evaporative cooling technologies to prevent heat strain from occurring. On the other hand we found that people should not use electrical fans (e.g., $V$ higher than 0.8 m/s) when indoor conditions exceed $t_o$ = 50 °C and $RH$ = 40 %, $t_o$ = 40 °C and $RH$ = 82 % or $t_o$ = 37.5 °C and $RH$ = 100 %. It should be noted that such extreme weather events are rare and may only occur in few locations across the world [23]. We also compared these data with the records available in the Emergency Events Database (EM-DAT) [25]. 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 117000 deaths, out of which a total of 102876 and 3803 people died during heatwaves

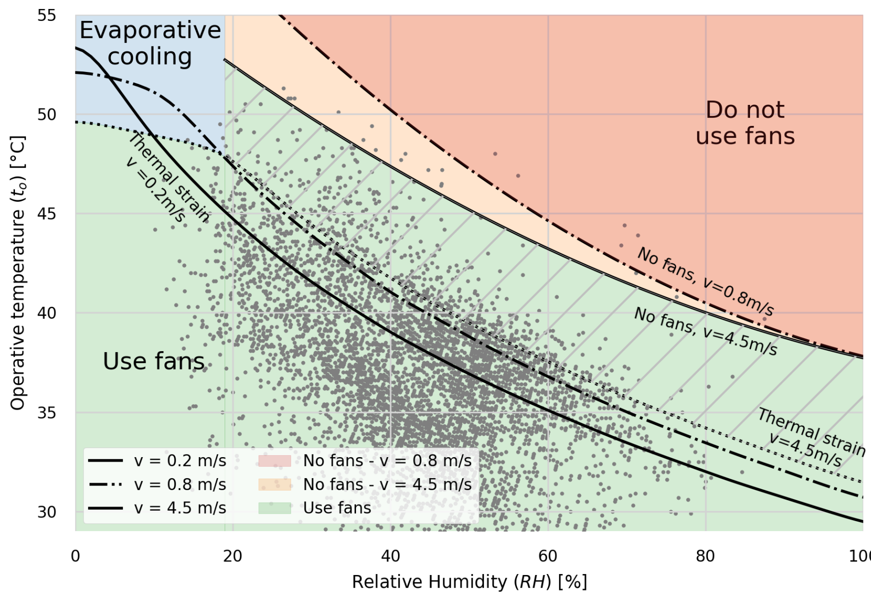


Figure 6: The green area shows the environmental conditions in which the use of fans is beneficial since they provide additional cooling to the human body. In the hatched area, while the use of fans it is still beneficial, people are most likely to suffer from heat stress. Finally the red area demarcates the region in which electrical fans should not be used. The dots show the maximum extreme climate conditions recorded over the last 10 years in more than 5000 locations worldwide. These results were calculated assuming $\overline{t_r} = t_{db}$, $I_{cl} = 0.5$ clo, $M = 1.0$ met.

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 than the use of electrical fans would have been beneficial in most of those scenarios.

Our results validate and extend the findings of Jay et al. (2015), who developed a simplified heat model to show that elevated air movements are beneficial even if $t_{db}$ exceeds skin mean temperature ($t_{sk}$). While the use of compressor-based cooling would arguably be more effective than electric fans in ensuring that people do not suffer from heat strain during heatwaves, it should be noted that in 2017 approximately 9.2 %, 24.1 % and 43.6 % of the world population lived with less than \$1.90, \$3.20 and \$5.50 per day, respectively. This number is expected to increase in 2020 due to the COVID-19 pandemic, and global warming is also estimated to increase frequency and intensity of heatwaves [26]. Sub-Saharan Africa and South Asia are the poorest regions of the world. They are characterized by high temperatures and is where climate change is expected to be an acute threat for the whole population [26]. These people who may have limited financial means, access to electricity, and water, should certainly not be discouraged to use fans when temperatures exceed 35 °C. In addition, poor people living in rural area may not have the opportunity to shelter themselves from heatwaves in publicly air-conditioned places. Similarly, in developed nations, where access to electricity is less of a concern, low income people, the elderly and people with varying types of physical disabilities are those who are mostly at risk during heatwaves, and may not be able to cool or leave their homes during heatwaves. Hence, they too should not be discouraged from using electrical fans.

During severe heatwaves, electrical fans may not alone be able to protect people from physiological strain, however, in most locations they would still provide some benefits, albeit marginal. All individuals should ensure that they keep themselves hydrated by drinking plenty of water, take cool showers or baths, wear light loose clothing, avoid physical activity, eat small cold meals, move to cooler areas of the home and do not expose themselves to direct solar radiation [8]. Electrical fans can be used in combination with conventional compressor-based air conditioning to increase comfort conditions indoors while increasing temperature set-points.

- Say there are no models who allow to estimate the benefit of elevated air speed under various environmental and personal factors.
- Talk about dehydration and the fact that with electrical fans $h_e$ increases, hence the $m_{rsw}$ does not significantly increases.
- List other strategies that could be used by people like evaporative cooling, ingestion of cold drinks and skin wetting.

In this manuscript we used an heat balance model that uses coefficients that were estimated empirically and some simplified equations (e.g., to calculate the respiratory losses) were used. Consequently, results may not be applicable to all individuals, such as those who are under medications or have pre-existing conditions.

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