Human Response to Heat Stress: Implications for Global Warming

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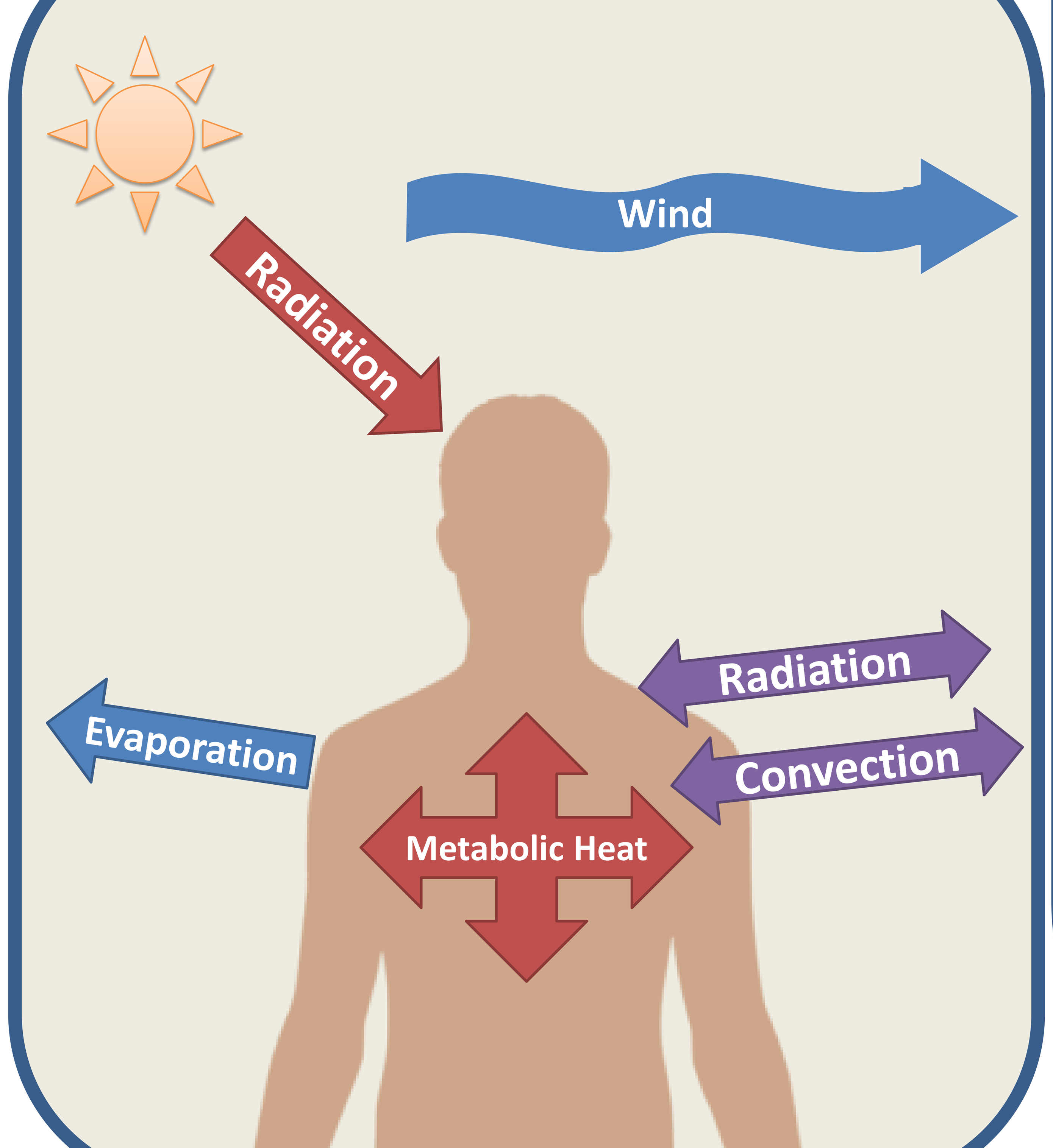
Abstract

Rising temperatures around the globe pose a threat to human life in many hot locations. Previous work on this subject by Sherwood and Huber[1] uses very rudimentary approximations to determine what conditions are life-threatening. Many environmental interactions such as sunlight and thermal radiation were ignored. This work attempts to develop a more complete model of human heat regulation based on physical principles for the purpose of evaluating the severity of heat stresses under given environmental conditions. A computer model is developed and tested against the more basic calculations from previous work, and differences are noted. In particular, the wet-bulb temperature required to reach lethal body temperatures is found to be lower than previously implied.

Figure 1: Outline of model processes



Introduction and Background

Wet-bulb temperature takes the dew point (relative humidity) into account, which makes it a good metric against which to compare heat stress. At high wet-bulb temperatures, it becomes impossible for the body to lose heat. Previous results claim that wet-bulb temperatures over 35°C are lethal to humans[1]. However, this is a best-case scenario, when a person is in ideal conditions for cooling themselves. According to data from NOAA for the past year, wet bulb temperatures in some inhabited parts of the world are already elevated over 31°C, which surpasses what was claimed by Sherwood and Huber and could be extremely dangerous for humans.

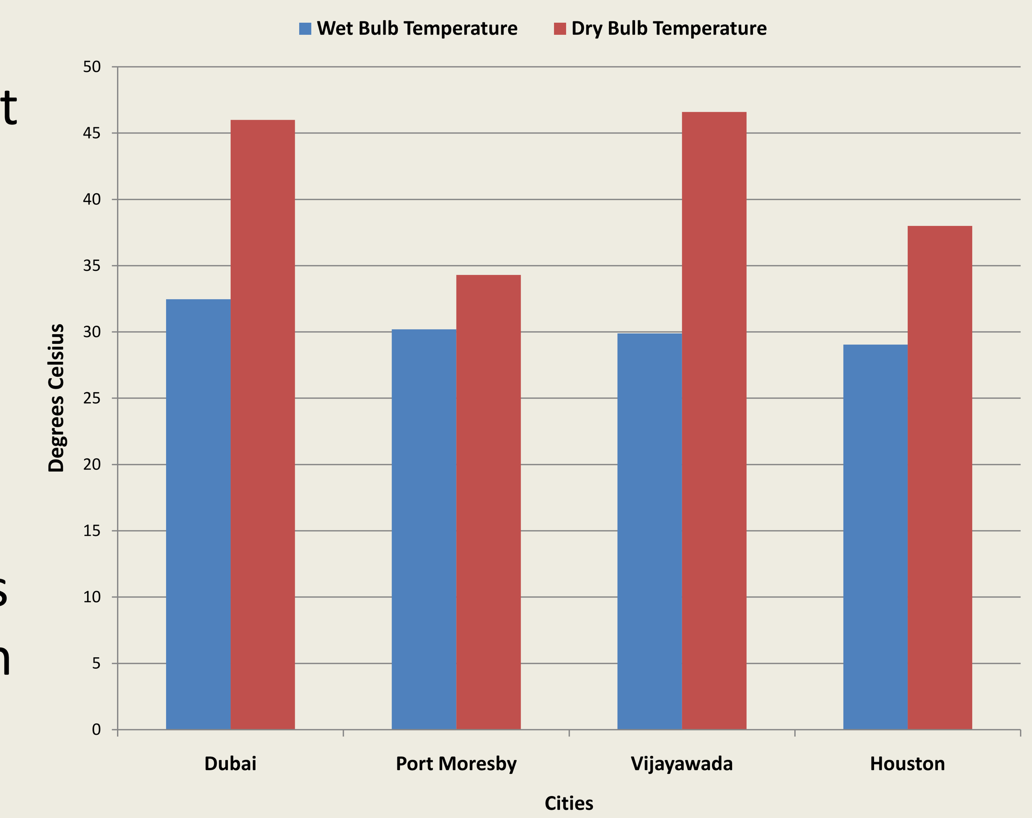


Figure 2: Highest wet-bulb and dry-bulb temperatures in select cities (2014-2015)[2]

Methods and Model

In the simulation, the major factors involved in human thermoregulation must be modeled and included. The Basal Metabolic Rate (BMR), also known as Resting Energy Expenditure (REE)[3]:

$$REE = 10m + 6.2h - 5a + x \quad \begin{cases} x = 5, & male \\ x = -161, & female \end{cases}$$

Where REE is in kcal/day. In this expression m is mass, h is height, and a is age. This is only for a person at rest. For various rates of exercise, other values are used for metabolic heat. Two of the largest exchanges with the environment are convective and evaporative heat transfer, E_c and E_{sw}, respectively[4]:

$$E_c = 8.3(T_{skin} - T_a)\sqrt{v} \quad W/m^2, \quad E_{sw} = 12.4(p_{skin} - p_a)\sqrt{v} \quad W/m^2$$

where T_a is the ambient temperature, v is the wind speed, p_{skin} is saturation vapor pressure at skin temperature, and p_a is ambient vapor pressure. Another important factor in the heat balance is black-body radiation, both emitted and absorbed by the body, the total being given by:

$$E_{bb} = \sigma(T_{skin}^4 - T_a^4) \quad W/m^2$$

Additionally, if the person is in direct sunlight they will have solar radiation incident on a portion of their body:

$$E_{sol} = 0.25 \cdot I \cdot (1 - k_{refl}) \quad W/m^2$$

Here the 0.25 factor is an angle-dependent factor to determine incident cross-sectional area[5], *I* is the intensity of sunlight (around 600 W/m² for a summer day), and k_{refl} is skin reflectivity.

These formulae were implemented in C++ in a real-time simulation of heat regulation over a range of environmental conditions, parameterized by (dry) temperature and wet-bulb temperature.

Discussion and Conclusions

The model was run for several different environmental conditions with varying temperatures and wind speeds. A good case to examine is an average person doing work (metabolic rate of ~500W). In all cases, the initial core temperature is 37°C (98.6°F). In one example similar to the heat seen in Dubai (T_{wb}=32°C, fig. 2), with moderate wind speeds the subject's core temperature rises above 41°C (105.8°F) in just over an hour, which would not be survivable. In still cooler conditions (T_{wb}=30°C), the simulated core temperature rises above 40°C in less than two hours and continues to rise to life-threatening levels. Based on the data, this simulated model suggests that lethal conditions can be encountered far below the previously proposed lethal wet-bulb temperature of 35°C. Even this simulation assumes some idealized conditions for body cooling, and so must be taken as optimistic.

References

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