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DEVELOPMENT OF A COMPUTER MODEL OF HUMAN HEAT STRESS WITH 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 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 compared with the results 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.

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Chapter 1

Introduction

1.1 Heat Stress

The concept of heat stress on the human body is one to which everyone can relate to some extent. It is a common experience to be outside on a hot summer day and experience pronounced fatigue in contrast to more temperate days. It is also common knowledge that it is not simply temperature which dictates how stressful the outdoors will be to one's body, but also other environmental factors, including humidity and the presence of a breeze.

Indeed, it is important to understand how all of the environmental factors combine to affect the heat state of the human body. Some of the most important contributions are metabolic heat expenditure, convective heat transfer, sweating and latent heat loss, the presence of sunlight, and black-body radiation. These are the processes that will be expounded upon in this thesis and worked together into a computer model of human thermoregulation. Before detailing these processes, motivation will be given for the subject at hand.

These notions may at first seem unimportant, as for most who live in the developed world, shelter from the elements is taken for granted. It may also seem to be of lesser importance, as hot summer days have existed for as long or longer than humanity itself, and up to this point have seemingly not posed a threat to human existence. However, as our understanding of climate change and humans' collective impact on it improve, heat stress is brought into the forefront as a potentially devastating predicament[1].

Many of the most prominent studies and results about global warming have been focused on oceanic effects and CO_2, such as sea level rise, erosion of coastlines, and ocean acidification[2][3][4]. This raises the question of humanity's ability to adapt to rapidly changing environments. However, this is more a question of whether we can technologically adapt, rather than referring to adaption of the human body itself. That is, whether we can make coastal cities more resilient, reclaim CO_2 from the atmosphere, etc. The rise of temperature itself is often presented as being detrimental by virtue of the fact that it contributes to the above processes.

A different subject is the actual adaptability of the human body itself, and its resilience to the rising temperatures across the globe. The answer may not be as clear - or as pleasant.

1.2 Climate Change and Adaptation Limits

By now it is commonly accepted that the Earth is warming, and human actions are driving this process[5]. Humans are able to adapt to changing climates, but only to a certain extent. The extent of human adaptibility is currently unknown, and stating an outright limit on what humans could handle is difficult.

An excellent paper addressing this topic was published in 2010 by Steven Sherwood and Matthew Huber. In it, they use the CAM3 climate model to predict mean surface temperatures throughout the globe in the future. From these results, they conclude that human inhabitance of certain currently-inhabited areas may be dangerous or impossible in coming decades due to warming caused by high atmospheric CO_2 concentration[6].

In their supplemental information, they very briefly detail the simplified model of heat stress which they used in their calculations. They define the *sensible* heat flux S from the body as $S = k(T_{skin} - T)$, while the *total* heat flux F is approximated by $S + L = k(T_{skin} - T_w) = F$. Here, T_{skin} and T are skin temperature and ambient temperature, and L is the latent heat lost through sweating. T_w is the wet-bulb temperature, a combined measure of temperature and humidty which will be discussed later. They then solve this set of equations and plug in relevant ambient conditions to see whether the temperature and water needs are feasible for a human being.

Based on this, Sherwood and Huber concluded that 35°C is the lethal wet-bulb temperature for sustained human environment. While this back of the envelope calculation is useful, it is very approximate. This lethal wet-bulb value essentially puts an upper-bound on survivable conditions. However, as will be discussed in this thesis, this value is optimistic. It will be the goal of this thesis to generate an improved model of human heat exchange to check this lethal wet-bulb approximation.

1.3 Wet-Bulb Temperature

Sherwood and Huber based their survivability criterion on a simple calculation involving the wet-bulb temperature. Wet-bulb temperature is defined as the temperature to which a parcel of air is cooled by evaporating water into it at constant pressure until saturation is reached[7]. The heat required to evaporate water into the parcel of air comes from the air itself, hence the wet-bulb temperature at given conditions is less than or equal to the "normal" temperature, or dry-bulb. If one were to cool air to saturation pressure without adding water vapor, the dewpoint temperature is reached. If the air is saturated with water, so that the relative humidity is 100%, then wet-bulb temperature equals dry temperature. So, the wet-bulb temperature lies between the dewpoint and the dry temperature.

From a more practical perspective, the wet-bulb temperature can be measured using a wet-bulb thermometer. As is implied by the name, the bulb of the thermometer is wrapped in a wet cloth, and is then ventilated until the thermometer reaches equilibrium temperature. This reading is approximately equivalent to the precise thermodynamic wet-bulb temperature[7].

Wet-bulb temperature is important here because it maps well to human heat stress. It is a combined measure of temperature and humidity, which are the defining factors that affect how well our body can cool itself. We will return to the topic of wet-bulb temperature in chapter 3 when computer implementation is discussed.

Chapter 2

Processes

2.1 A Basic Model

The present goal is to formulate a model (albeit simple) of human thermoregulation. This primarily involves accounting for the various ways in which the human body exchanges heat with the environment. The focus of this work is towards how the body deals with extreme heat situations, and as such we will not be concerned with the body's internal mechanisms for warming itself, such as shivering other internal responses. However, there will be a basic treatment of one of the body's major internal responses to a heavy heat load, namely vasodilation. The purpose of this chapter is to enumerate and explain each process that will be included in our model.

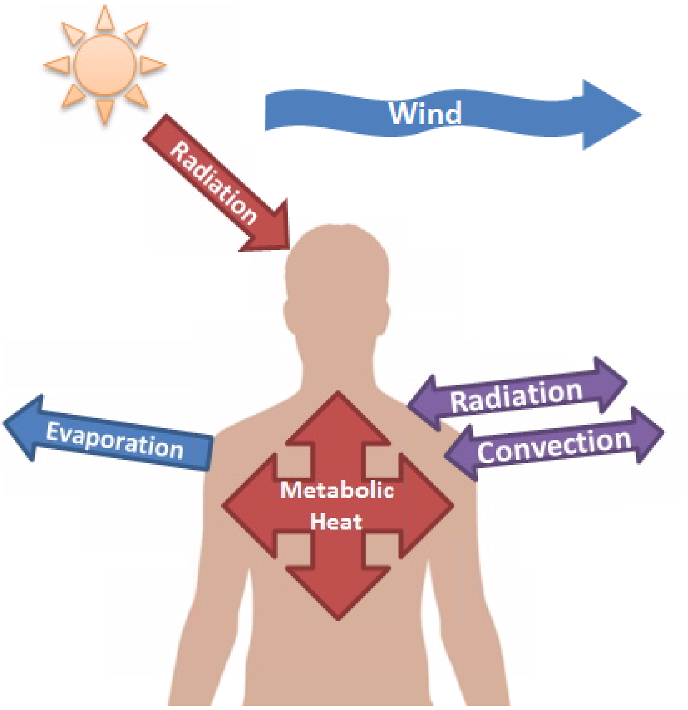

Figure 2.1: Basic illustration of the major thermodynamic processes which exchange heat with the environment

2.2 Basal Metabolic Rate

The first important heat value is the metabolic heat generated by a person simply by being alive, while not undergoing any type of strenuous activity. This value is obtained from the Basal

Metabolic Rate (BMR), also known as Resting Energy Expenditure (REE), an equivalent term. This is the minimal amount of energy that the body expends simply to accomplish basic body functions at rest. The value can vary noticeably from person to person, depending on age, biological sex, body mass, and height.

There are a number of ways to approximate this resting expenditure, however one of the most widely used is that from Mifflin, et al [8], who give the following formula for resting energy expenditure:

$$E_{REE} = 10m + 6.2h - 5a + x. \tag{2.1}$$

In this equation, m is body mass in kilograms, h is height in centimeters, and a is age in years. The value of x is used to differentiate between male and female energy expenditures, where the value of 5 is used for males and -161 is used for females. The result E_{REE} has units of kilocalories per day. The formula is determined from an empirical fitting, so the constants in front of parameters are defined such that they have the proper units to give a result with units of power.

2.3 Sensible Heat

Sensible heat flux is the process by which air which has been heated by the body is carried away, thus taking body heat along with it. In the biological literature, sensible heat flux is more commonly called convective heat transfer[9][10]. This can also work in the reverse, where hot air from the environment deposits heat into the body. This mechanism of heat transfer can be driven more quickly by the wind speed, and as such the mathematical form it will take must be a function of wind speed.

At the surface of the human body, air currents become turbulent, as is common when fluids flow across an uneven surface, such as skin covered with hair. As such, the dependence of the convective heat transfer on wind is best determined empirically, where it has found to be related by the square root. Wheeler[9] states it as follows in Eqn. 2.2.

$$H = k_c(T_s - T_a)\sqrt{v} \tag{2.2}$$

Here, T_a is the ambient air temperature, which is taken to be approximately constant. T_s is the current skin temperature of the body, and v is the wind speed. k_c is the convective constant, which is determined empirically. H has units of power per square area, and as such it must be multiplied by the total body surface area to acquire the total rate of energy transfer between the body surface and the air.

Body surface area (often abreviated BSA) will be useful several times in this thesis, and so we will introduce a common formula for approximating it here. The DuBois formula is one of the most widely used for this [11], and is given in Eqn. 2.3.

$$A_{BSA} = 0.007184 \cdot m^{0.425} h^{0.725}. \tag{2.3}$$

Here m is body mass in kilograms and h is height in centimeters. The result A_{BSA} is in units of square meters.

2.4 Sweat and Latent Heat

For humans facing oppressive heat, sweating is one of the most important mechanisms of the human body, as it allows us to shed heat through the evaporation of water from the surface of the skin. As air passes over wet skin, some of the water (which is assumed to be at skin temperature) will evaporate. The latent heat required for this vaporization process is drawn out of the body, thus cooling it. This process is obviously also very dependent on wind speed, as the more air that passes over the skin, the more opportunity there is for the evaporation of sweat.

Apart from air speed, what drives this evaporation is a concentration gradient. As long as the water vapor concentration of the air is low enough, evaporation will occur. However, this also implies that if there is too much humidity in the air, heat loss through sweating will break down. The energy transfer from sweating is well-described by Kerslake [8] in Eqn. 2.4:

$$E_{Sw} = k_e(e_s - e_a)\sqrt{v}. \tag{2.4}$$

In this equation, e_s is the saturation vapor pressure at skin temperature, and e_a is the current ambient air vapor pressure. Once again, v is the wind speed and k_e is an empirically determined constant, and we must multiply E_{Sw} by A_{BSA} (Eqn. 2.3) to get the total energy transfer.

2.5 Solar Heating

If a person is outside, unshaded on a clear day, they will be in the presence of direct sunlight. Based on the angle of the sun in the sky and orientation of the person's body with respect to the sunlight, some fraction of this incident solar radiation will be absorbed, and the rest reflected. The sunlight which actually arrives at the surface of the Earth is highly variable, depending on latitude, time of day, and the current season.

On average, the solar radiation arriving at the top of Earth's atmosphere is 1366 W/m^2 based on simple calculation and measurements[12]. The solar energy flux that reaches the Earth's surface is significantly reduced by atmospheric processes including scattering, absorption, and reflection. The approximate maximal solar flux at the surface is less than 1000 W/m^2[13]. From this, some basic geometry and trigonometry can allow us to calculate the approximate solar flux at different latitudes on a sunny day. As this model is simplified and not concerned with variations throughout the day, a body in direct sunlight is assumed to be exposed to the sensible value of 500 W/m^2 of solar energy flux.

The total surface area of the body A_{BSA} is not directly exposed to the Sun's rays. Rather, a cross-sectional area of the body would be the area exposed to solar flux. Wheeler used projection photography to approximate the percentage of body area exposed for an upright humanoid, and found that based the angle of inclination it varies between about 23% and 7% of total body surface area [14].

Another factor in energy absorbed from solar radiation is skin color. Depending on a given person's skin albedo, more or less solar radiation will absorbed or reflected. This can be accounted for by multiplying the incident solar radiation on the skin by the proper skin reflectivity. A table of such values for different populations can be found in the referenced article by Jablonski and Chaplin[15].

2.6 Black-Body Radiation

Black-body radiation is the electromagnetic radiation emitted from a perfect radiator heated to some fixed temperature. The spectrum of radiation, and hence the total power emitted this way is dependent on the surface temperature of the body (in this case, an actual human body).

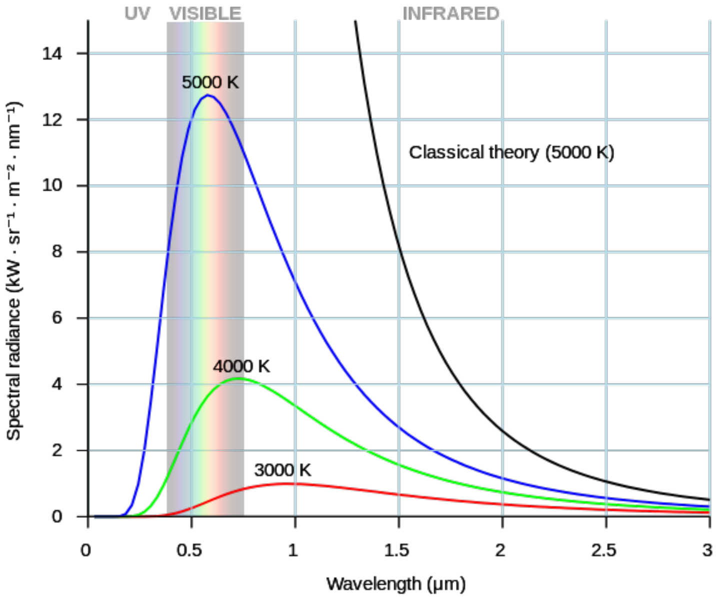

Figure 2.2: Example black-body radiation spectra for various temperatures. Public domain work

The total power radiated per unit area is proportional the temperature raised to the fourth power. This is known as the Stefan–Boltzmann law, shown in Eqn. 2.5.

$$P = \epsilon \sigma T_s^4 \tag{2.5}$$

Since this is again a power flux, it must be multiplied by body surface area to calculate the total power emitted. The factor of ϵ in Eqn. 2.5 is the emissivity. While the body will radiate energy away in this manner, if it is assumed that the surrounding objects in the environment reach some steady ambient temperature, then the person will absorb energy from the environment at a rate which takes the same form as above, but with ambient temperature instead of skin temperature.

2.7 Core and Shell

It is useful when looking at temperare regulation to consider the body as being composed of two loosely-defined parts: the core and the shell[8][10]. The core temperature is maintained nearly constant at the body's set-point temperature and varies more slowly. The shell, on the other hand, is the less massive exterior parts of the body, whose temperature varies more readily with the surroundings.

The environmental heat exchanges and processes discussed thus far take place at the interface of the shell (the outer layer and skin) and the ambient environment. Heat is then transported between the shell and the core mainly via the circulatory system. Hoppe provides a parameterization for blood flow between the core and shell of the body[10], shown in Eqn. 2.6.

$$v_b^* = \frac{6.3 + 75(T_c - 36.6)}{1 + 0.5(34 - T_s)} \tag{2.6}$$

This expression, which gives v_b^* in units of 1/(hm^2), is reasonable for humans in "nice" environments. However, as can easily be seen, v_b^* diverges to infinity as skin temperature approaches 36°C. For the hot environments we will treat, this is a reasonable skin temperature to be reached. Therefore it is necessary to cap this blood flow at a certain point so that it does not diverge to infinity, but rather levels off to some constant high value. A reasonable fitting is shown in Fig. 2.3 as a function of T_s for a particular value of T_c. The expression is given in Eqn. 2.7. By multiplying this by an approximate area of the interface of the core and shell and the heat capacity of blood (approximately 3860 J/kgK [16]) and finally by the temperature difference between core and shell, we have the energy transfer between core and shell, f_c.

$$v_b = (2.07T_c - 75.44)\cdot(\frac{100}{\pi}\arctan(0.75(T_s - 34.7)) + 53) \tag{2.7}$$

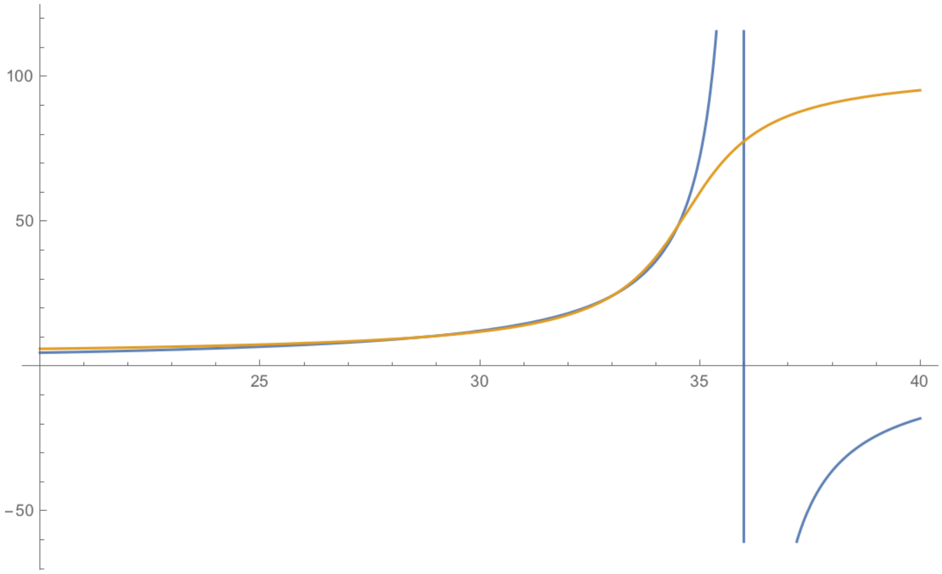

Figure 2.3: A reasonable fitting to Hoppe's blood flow equation which does not diverge (orange). The Hoppe curve in shown in blue.

The body therefore can be considered as two components which exchange heat by the circulation of blood. What fraction of the body is considered to be the core versus the shell varies with body temperature as well. For higher temperatures, blood flow increases, and the shell becomes effectively thinner. Hoppe quantifies this by the following Eqn. 2.8[10].

$$\alpha = 0.044 + 0.35/(v_b - 0.1386) \tag{2.8}$$

The parameter α is the dimensionless fraction of shell mass to core body mass.

Chapter 3

Computer Implementation

3.1 Quantities of Interest

Since we wish to compare our results to that of previous work, it is a good idea to use the dry and wet-bulb temperatures as the parameters determining the environmental conditions. However, in the previous chapter, we made no use of wet-bulb temperature.

In Eqn. 2.4 from the previous chapter, which calculates heat lost through sweating, we used ambient vapor pressure and saturation vapor pressure. These values must be calculated from dry temperature and wet-bulb temperature. The derivation of these relationships is rather involved, but can be read in texts such as those by Emanuel[17] or Bohren[7]. Saturation vapor pressure can be uniquely determined for a given temperature, and is shown in Eqn. 3.1 from Emanuel's text *Atmospheric Convection*.

$$e_s = 6.112e^{\frac{17.67T}{T+243.5}}. \tag{3.1}$$

Here e_s is in millibars and T is in degrees Celsius. Our latent heat loss equation also requires calculation of the actual vapor pressure for a given temperature and humidity. Humidity of the environment is carried in the wet-bulb temperature, and Eqn. 3.2 gives vapor pressure as a function of dry temperature T_a and wet-bulb temperature T_{wb}, as detailed in Bohren and Albrecht's text *Atmospheric Thermodynamics*[7].

$$e = e_s - \frac{pc_{pd}}{\epsilon l_v}(T_a - T_{wb}). \tag{3.2}$$

This is called the psychrometric equation. The cluster of constants $\frac{pc_{pd}}{\epsilon l_v}$ refer to physical properties of the air which is known collectively as the psychrometric constant, and at sea level is approximately 0.65 millibars/K.

Using these equations, we can use the equations from the previous chapter in our model while still parameterizing the environment using dry and wet-bulb temperatures.

3.2 The Model

The equations of the previous chapter are largely energy fluxes. These fluxes, when multiplied by body surface area, give the rate of energy exchange in Joules per second once the appropriate conversion factors are applied. Therefore we can think of the sum of all of these values as the energy exchanged over the course of one second.

The energy flux into the shell is then $F_s = S + f_c - H - E_{Sw} - P$, where S is solar radiation, and P includes both the leaving black-body radiation and the incident environmental radiation. A positive value indicates energy storage in the shell. The energy flux into the core is $F_c = E_{REE} - f_c$. Again, a positive value indicates energy storage.

These energy values can be translated into temperature increase or decrease according to the average heat capacity of human flesh, C, which is slightly lower than the heat capacity of blood. Then we have that at each "time step":

$$T_s = T_s + \frac{F_s}{C\alpha m} \tag{3.3}$$

$$T_c = T_c + \frac{F_c}{C(1-\alpha)m} \tag{3.4}$$

As will be mentioned in the next section, this does not describe the exact time dependence of the system, but rather should be taken as an approximation which can be used to iterate toward the steady-state solution.

3.3 Fixed-Point Iteration

Many of the equations presented in chapter 2 are precisely valid only at equilibrium conditions. That is, the state when energy fluxes are constant and temperatures are fixed. These equations therefore are only approximate for conditions outside of equilibrium. We are interested in finding the equilibrium core body temperature for given environmental conditions, given some initial guess. One way of accomplishing this is the method of fixed-point iteration[18].

By definition, a number c is a fixed point of a function f if $f(c) = c$. The process of fixed-point iteration is then simple:

Choose an initial guess x_0. The next value x_1 is given by $x_1 = f(x_0)$. This process is then iterated, where at each step i we have that $x_{i+1} = f(x_i)$. The iteration process can be halted when the difference between two subsequent iterations has reached some specified tolerance value. In psuedocode, the process is essentially the following once the initial value is chosen:

```
while x - xp < Tol
    xp = x
    x = f(x)
```

For locally convergent functions f, fixed-point iteration in general converges linearly.

The model we described above is well-suited for the application of fixed-point iteration, as it is already in the explicit form of $x = f(x)$.

3.4 Results

The model was coded in C++ and run over various conditions in order to observe how the simulated body would equilibriate under chosen conditions. A plot of three runs of interest is shown in Fig. 3.1. All three runs in this plot were calculated under identical ambient conditions (dry temperature, wind speed, sunlight, body attributes held constant) for varying wet-bulb temperatures. What varies between the plotted runs is the level of metabolic activity. This allows us to see how the body is predicted to deal with varying activities in difficult climates.

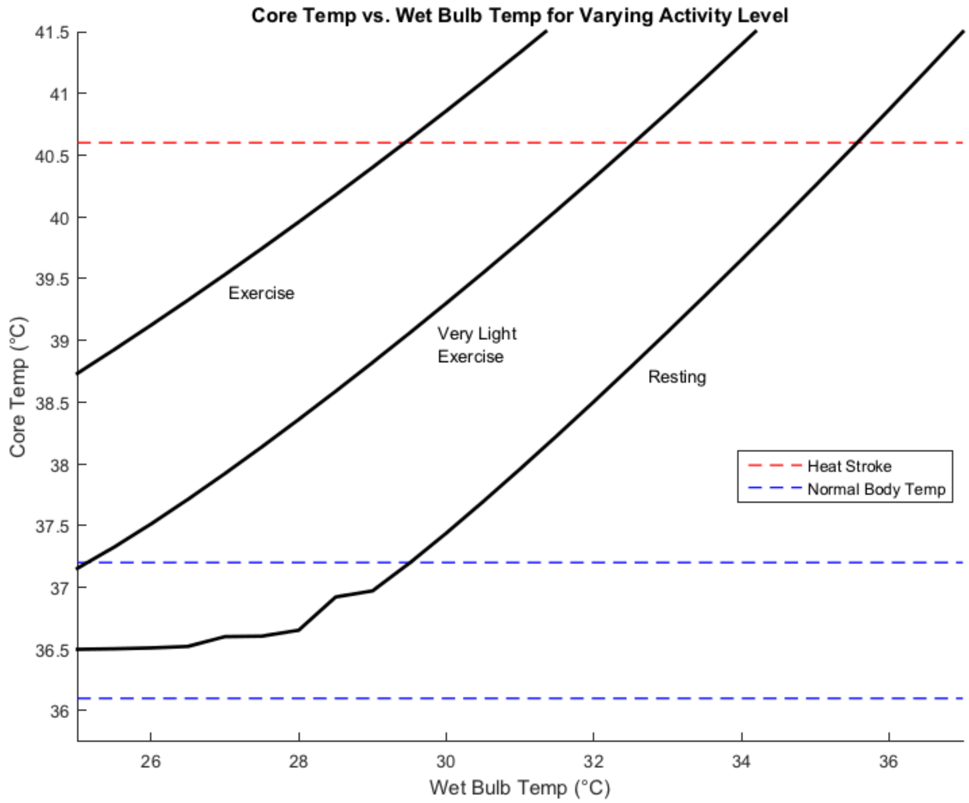

Figure 3.1: Steady-state core body temperature as a function of wet-bulb temperature for three metabolic cases

Although “normal” body temperature is often quoted to be 98.6°F (37°C), this is really an average value. Typical healthy core body temperatures exist in a range between approximately 36.1°C and 37.2°C[19]. These values are indicated on the plot above as dashed blue lines. The dashed red line indicates the temperature threshold generally used for diagnosis of heat stroke[20].

The runs above simulate the typical body for a 25-year-old male with a height of 180cm and weight of 80kg. For all three of these runs, the ambient dry temperature is fixed at 40°C, and the surface wind speed is taken to be 1 m/s. In the first run, labeled ”Resting”, the metabolic heat generation is taken to be the Basal Metabolic Rate. As can be seen, for a range of wet-bulb temperatures below about 30°C, the body’s equilibrium core temperature is maintained steadily around normal body temperature. Past this point, the equilibrium core body temperature rises steadily above what is considered to be a healthy core temperature. The equilibrium temperature curve crosses the heat stroke boundary shortly before the 36°C wet-bulb temperature mark. Sustained core body temperature above this level is likely to result in death.

The next plotted curve is labeled “Very Light Exercise” and corresponds to a metabolic heat production of 300 Watts, which is approximately 4 times basal metabolic rate. This would correspond to a level of exercise slightly higher than a brisk walk[10]. For this run, extremely dangerous core body temperatures are encountered for wet-bulb temperatures just above 32°C. The last curve on this plot is for a metabolic rate corresponding to heavier exercise, akin to a sport or jogging. The potentially lethal core temperatures set in at even lower wet-bulb temperatures.

Chapter 4

Discussion and Conclusion

The simulation runs presented in the previous chapter offer much material to examine. There are a few things to note about the results before discussing the implications.

The plotted curves and simulation runs represent approximate equilibrium values for core body temperature. This implies that the body is subjected to these conditions for a significant duration and the interactions have reached steady state. For the cooler scenaries far away from dangerous temperatures, this is realistic. However, for the runs that enter dangerous territory, it may not be entirely accurate to describe them as "equilibrium." The body would not be able to indefinitely sustain itself in those conditions. Eventually, exhaustion would set in, and the normal body process outlined in this thesis may break down. In the extreme conditions, an obvious implication here is that the person would not survive.

With those notes aside, this model does imply a somewhat, harsher, bleaker picture than previously implied. It does appear true that for a human who is completely at rest, the lethal wet-bulb temperature lies around 35°C. However, for activity levels slightly beyond this, the onset of lethal body conditions is rapid. It seems overly optimistic to say that an area would be safe to inhabit for wet-bulb temperatures below 35°C. Some level of moderate activity is required for normal life, and the lethal conditions are reached much sooner in these circumstances.

It should also be noted that these values are still somewhat optimistic themselves. The model presented here assumes that the body is perfectly coated in a thin film of sweat that allows evaporation to happen continuously over the whole body. This is a bit unrealistic, and carries with it the requirement that people must have access to large water supplies. In the areas where one might encounter these conditions, access to ample clean water is not a guarantee.

This lowering of the bound on survivable conditions has implications for the future projections made by others. The areas of the world which may not be humanly inhabitable could be larger than previously estimated. If climate change continues unmitigated, our planet may become a very different, more dangerous place for humans to inhabit. Useful future work in this topic could be to couple a more complex human heat simulation like this to a climate model directly, to gain more precise boundaries on the regions of human survivable in projected climates.

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PERSONAL PROJECTS

Phase Plotter Available on Website

Phlotter, or Phase Plotter, is a small and fast program for making simple phase diagrams of two-by-two systems of ODEs. The program is written in C++ utilizing SFML for graphics and input, and using Lua for configuration.

COMPUTER SKILLS

Proficiency in C++, Java, MATLAB
Some experience with PHP, Lua, Python
Experience with Windows, CentOS, Ubuntu (Desktop and Server)

HONORS AND AWARDS

Teas Scholarship, Full Tuition (2015-2016)
Finalist in Penn State New York Times Speaking Contest, Top 6 of over 1000
Bert Elsbach Honors Scholarship in Physics (2014-2015)
Phi Beta Kappa, Lambda Chapter of Penn State
Sigma Pi Sigma Physics Honor Society

EXTRACURRICULAR ACTIVITIES

Sigma Pi Sigma Induction Co-Chair
CodePSU and HackPSU Participant
Society of Physics Students
Penn State Association of Computing Machinery