# Heat: A Primer for Public Health Researchers

Glenn R McGregor (MSc, PhD)
Department of Geography
Durham University
Stockton Rd
Durham DH1 3DE
United Kingdom
email: glenn.mcgregor@durham.ac.uk

and

Jennifer K Vanos (BSc, PhD)
Scripps Institution of Oceanography
& School of Medicine
University of California
San Diego
USA

## Abstract

Human exposure to heat has emerged as a major public health concern, yet the term ‘heat’ is often conflated with high temperature. Heat, as recognised in the field of human biometeorology, however is a complex phenomenon resulting from the interaction of a range of environmental variables. The objective of this paper therefore is to provide a primer on the physical characteristics of heat from a biometeorological perspective for those interested in the epidemiology of extreme heat. Heat strain takes the form of a range of physiological responses and subsequent health outcomes, such as a rising body core temperature and heat stroke. Heat strain occurs as the response due to a positive imbalance of excess heat imposed on and/or created by the body. Thus, it is consequent upon the synergistic effects of air temperature, humidity and ventilation levels, radiation loads, and metabolic activity. It therefore follows that air temperature alone is seldom the reason for heat stress. This primer suggests that the conceptualisation of heat stress is best described with reference to the human heat balance (HHB), which describes the balance between all heat gains and losses and whether the body experiences a heat surplus or deficit for a given set of environmental and human behaviours. The HHB also facilitates an understanding of the various avenues of heat gain/loss. In order to assess levels of heat stress, empirical, direct and rational heat stress indices have been developed with the latter based on the concept of the HHB. This primer presents some of the more commonly used heat stress indices, differentiates between individual and population heat stress exposure, and draws attention to some of the challenges associated with formulating meaningful assessments of heat stress for public health.

Keywords: Heat stress; human heat balance; personal heat exposure; heat strain; human biometeorology; epidemiology of extreme heat.

## 1. Introduction

The human body deals with a range of atmospheric stressors including heat, environmental radiation and air pollution. Either singularly, or in combination, these may affect the physiological and/or psychological wellbeing of an individual on a range of time scales. Notwithstanding the importance of environmental radiation or air pollution, heat has become an increasing challenge for public health as demonstrated by the occurrence of major fatal extreme temperature events in many countries.[1] Added to this is the spectre of an increased frequency of extreme heat events related to human induced climate change[2]; worryingly, there is mounting evidence that some recent public health significant heat events can be partly attributable to human-related increases in global temperatures.[3–5]

There is a burgeoning literature on the health impacts of heat and its management.[1] However more often than not, and perhaps implicitly rather than explicitly, heat-health studies outside the discipline of human biometeorology[6] frequently assume 'heat' to mean 'high temperature', even though heat as a physical term is a complex phenomenon resulting from the interactions of a range of environmental variables. Given this, the purpose of this paper is to provide a primer, from a human biometeorological perspective, on the nature of heat in a human health context. Accordingly, this paper is organised as follows: Section 2 defines heat; Section 3 introduces and describes the concept of the human heat balance; Section 4 details common methods for assessing levels of heat stress, including those classified as empirical, direct and rational; Section 5 outlines the conclusions and public health importance. As this paper only provides a primer on heat, a systematic review of the literature on heat and health is not be presented here. Rather, this primer defaults to the related papers in this special issue for more detail on the impacts and management of heat as a public health issue.

## 2. What is Heat in a Health Context?

Although heat and temperature are often conflated to mean the same thing, in strict definitional terms, heat and temperature are different as summarised in Table 1. Heat is energy in the process of being transferred from one substance or object to another (moving from hot to cold). Following its transfer, heat is stored as internal energy in the receiving object. A change in the level of stored energy can be recorded in the form of a temperature change. In a human health context, as explained more fully in the next section, energy or heat can be transferred to the human body from the surrounding environment by conduction, convection and radiation. Therefore, a rise in body core temperature (BCT) occurs if the environment imposes significant heat gain on the human body that cannot be offset by heat loss (e.g. evaporation).[7]

**INSERT TABLE 1 HERE**

Heat stress is a common term used in heat and health studies. In human health terms, heat stress is the negative effect of the thermal energy (heat) environment on an individual. As a response to heat stress, the body exhibits strain (see Figure 1), which describes actions the body undergoes in responding to the increased heat load (e.g., increased skin or core temperature).[8] However, heat strain in the form of rising skin temperature and sweat rate will precede a rise in BCT (indicative of heat stress), and when the BCT does begin to rise, it is often environmentally-driven.[9] While most thermal energy resulting in heat stress transfers from the surrounding environment, excessive physical activity in warm-hot environments can produce what is known as exertional heat stress or illness[10] through the heat produced by metabolic activity. When combined with external heat stress, major heat strain can manifest by a rapidly rising BCT and a range of heat illnesses which, in increasing order of severity, are heat rash, heat oedema, heat syncope, heat cramps, heat exhaustion and life-threatening heatstroke.

**INSERT FIGURE 1 HERE**

The main components influencing external heat gains are atmospheric temperature, radiation, wind speed (ventilation) and humidity. Air temperature is important because it reflects the level of heat in the air resulting from sensible heat transfer (i.e., transfer of energy as heat without a phase change) mainly from the earth's surface into the lower layers of the atmosphere, although in urban environments sensible heat transfer from vertical surfaces is also important. As described by Davis et al.[11] humidity may play one of two roles as a component of heat stress. First, low levels of atmospheric moisture can facilitate high evaporative losses from the skin surface, which facilitates body cooling. However, uncontrolled rates of sweating may lead to life-threatening dehydration and the halt in sweating, which can also drive up BCT. Alternatively, high levels of atmospheric moisture may inhibit evaporation rates thus rendering the sweating process impotent as a heat loss mechanism (also termed 'inefficient sweating'). With respect to public health, individuals that are young, old, sick, and/or on medication may have compromised sweating and/or thirst response, and thus require increased monitoring during heat events.[12,13] Ventilation, a product of wind speed or atmospheric turbulence, normally helps to remove heat from the body by turbulent heat transfer. This type of heat loss occurs when the air temperature is less than skin temperature (which normally remains around 36°C). Yet when air temperature rises above that of skin, ventilation adds heat to the body *via* convection. High (low) rates of ventilation can also assist (hinder) skin-to-atmosphere evaporation rates, which are largely controlled by skin-to-air vapour pressure gradients.[14]

In a heat and health context, radiation refers to the radiant energy (non-ionizing) emitted from a radiating object such as the sun or a nearby surface. Radiation travels from the emitting object to the receiving surface (e.g. skin, earth) in the form of electromagnetic waves. Radiant energy generally takes two forms as defined by wavelength: shortwave and longwave radiation. In simple terms the 'hotter' an object the shorter the wavelengths of electromagnetic radiation emitted; the sun emits shortwave radiation whereas the earth's surface, as do our bodies, emits longwave radiation. These electromagnetic waves do not represent sensible heat, and thus are not recorded as a temperature by a sensor. Instead, radiation is either absorbed or reflected. The amount reflected is dependent on the surface reflectivity, or albedo. The average albedo of a human ranges from 20% (dark skin tones) to 45% (light skin tones).[15,16] Radiation that is not reflected is absorbed. If absorbed, the radiation will 'excite' the molecules in the surface layers of the skin or clothing and consequently raise the heat content and thus the temperature. The skin or clothing surface then emits approximately 95% of this absorbed radiation as longwave energy.[17]

The balance between all short and longwave radiation received and lost from the body's surface is the body's net radiation balance (R), which is an important component of the human heat balance (see next section). R represents the energy available for several processes at the skin surface, namely: (i) raising the air temperature immediately above the skin surface *via* sensible (turbulent) heat transfer to the atmosphere, (ii) undertaking evaporation of sweat from the skin surface by latent heat (turbulent) transfer to the atmosphere, and (iii) the conductive transfer of heat from the skin surface to the layers beneath the skin and the eventual transfer of this heat to the body core by the circulatory system. Importantly, a low humidity environment—while less stressful overall to the body—often coincides with intense radiation levels (clear skies) and enhanced sweat loss without visible signs of sweat (i.e., droplets on skin).[18] The bio-feedback between BCT and sweat rate (Figure 1) will therefore differ in humid versus dry environments, where enhanced cooling and loss of sweat (risking dehydration) occurs in dry conditions,[19] yet less cooling occurs in humid conditions with 100% RH at skin.[20] Such examples support the use of rational indices that can calculate maximum and required evaporation.[20–22]

Together, the synergistic effects of air temperature, humidity and ventilation along with either direct or indirect radiation loading of the body surface determine the level of personal heat exposure (PHE) which has been defined by Kuras et al.[23] as the *"realized contact between a human and an indoor or outdoor environment in which the air temperature, radiative load, atmospheric moisture content, and air velocity collectively pose a risk of increases in body core temperature and/or perceived discomfort".* Defined in this way, PHE is an important step of the conceptual pathway linking climate drivers and indoor and outdoor environments to thermal discomfort and adverse health outcomes.[23] PHE focuses on the microscale influences of a human's environment, whereas the 'air mass' concept—used by synoptic climatologists–

–describes the physical characteristics of the 'envelope of air that surrounds us' at a regional level, arising from the synergistic effects of weather variables. This concept has been used widely in biometeorological studies of heat and health.[24,25]

## 3. Human Heat Balance

The human heat balance (HHB) refers to the balance between all heat gains (losses) to (from) the body.[26] It is a key concept for understanding the flows of heat that influence BCT. In relation to this, heat tolerance—defined as the ability of the body to maintain a safe BCT–is both the reason for and the result of thermoregulation,[27] and is controlled by a combination of physiological and environmental variables. In addition to the atmospheric variables described above, the interplay of behavioural parameters of metabolic rate and clothing are crucial in determining the HHB and thus BCT.[28,29] Common average metabolic rates (and MET equivalents) include sleeping (46 $Wm^{-2}$; 0.8METs), standing (87 $Wm^{-2}$; 1.5METs); walking (114 $Wm^{-2}$; 2.0METs); running (542 $Wm^{-2}$; 9.5METs ), with more accurate estimates possible with advanced personal measurements.[30] The intricate balance of these environmental and behavioural factors supports the definition of PHE (defined above) and also reinforces the reality that the commonly-used predictors of air temperature and humidity alone are seldom the reason for an individual entering into classical or exertional heat stress. Rational indices that make use of the HHB establish the balance of simultaneous transfers (fluxes) of heat to and from the body effectively balancing to give a surplus (+$\Delta S$), deficit (–$\Delta S$), or a balance ($\Delta S = 0$) of energy storage per unit area of the human body per time (W $m^{-2}$).

$$0 = \Delta S + M + K + R \pm C - E \qquad [1]$$

Under daytime fair-weather outdoor conditions, heat gains include the metabolic heat flux (M), conductive heat flux (K), and net radiation (R) experienced by a human as well as convection (C) if air temperature rises above that of the skin, while the losses include convective heat loss (C), and evaporative heat loss (E).[14,31] Models employing the human heat balance concept for predicting heat stress or specific strains (sweat rate, skin or core temperature, etc.) must adequately account for an individual's personal attributes, acclimatization, and location (region and micro-climates) to be properly applied to heat stress prediction.

**INSERT FIGURE 2 HERE**

## 4. Assessment of Heat Stress

### *4.1 Measurement of heat stress variables*

Quantifying heat stress either by measuring the main heat stress variables or solving the HHB in a given place and time often requires fine scale microclimate (1m–1000m) observations, particularly in urban areas where wind and radiation change quickly over small distances[32] and large intra-urban variations in heat stress and radiant temperature can occur.[33,34] Unfortunately most cities lack the requisite high density networks for meaningful assessments of intra-urban heat stress, although the situation is changing.[35–38] Further, high-resolution urban numerical weather model outputs are increasingly applied for assessing heat stress.[39,40] Regrettably, most heat and health studies continue to rely on data from near-by airport weather stations which are unrepresentative of outdoor/indoor urban environments. The absence of standardised instrumentation and approaches is also an issue.[41,42] Common instruments and methods for measuring or estimating environmental variables are presented in Table 2.

**INSERT TABLE 2 HERE**

*4.2 Common Heat Indices*

Heat stress indices are used to predict/assess the physiological strain from stressful thermal conditions as outlined in Section 2. According to Havenith and Fiala,[26] the ideal heat-stress-assessment must consider all aspects of heat generation inside the body and all pathways for heat exchange between the body and the environment. Each index provides a single value that is interpreted along a scale that often represents neutral-to-dangerous conditions. Three types of heat indices exist, with various examples of each listed in Table 3:

**Empirical:** Based on verifiable observations or measurements of human physiological response to various factors of metabolic and environmental loads.

**Direct:** Simple and practical, based solely on measurements of weather conditions to infer the thermal environment experienced by a human using practical guidelines. Direct indices do not assess physiological responses.

**Rational:** Complex mathematical models that integrate both environmental and physiological variables, combining aspects of both empirical and direct indices. Rational indices employ the HHB equation and are more complex than direct or empirical indices. Rational indices are useful for understanding human thermal environments, specifically for estimating indoor/outdoor thermal comfort,[43,44] urban design,[45,46] exertional heat illness,[47,48] and occupational heat exposure[49]. However, they are less useful in large epidemiological studies due to the lack of fine-scale weather and personal information.

Below, we provide descriptions of common heat indices used for public health and well-being studies. Information for these and related indices used world-wide is also provided in Table 3. In-depth reviews of the history, limitations, and nature of over 50 indices are available elsewhere.[26,31,50–53]

**INSERT TABLE 3 HERE**

***Heat Index (HI) and Humidex (HX)*** are direct indices, empirically derived from air temperature and humidity to convey a 'feels like' temperature to the public. The HI is a simplified hot weather version of the Apparent Temperature—a rational index based on the HHB concept.[54] The HX was similarly developed for warnings and advisories.[55] Neither index, or their guidelines, account for metabolic activity or clothing and are thus most applicable to sedentary situations, as underestimation of heat stress may arise for active individuals.[56]

*The* ***Universal Thermal Comfort Index (UTCI)*** *is* a dynamic multivariate rational model, referring to the time dependency of the physiological responses prior to reaching a steady state.[57] The final output compares a response environment to a reference environment across a range of air temperatures ($T_a$) (–50 to +50 °C). The reference environment is based on a constant metabolic heat load (2.3 METS or 135 W $m^{-2}$), wind speed (0.3 m $s^{-1}$ at 1.1m height), walking speed (4km $hr^{-1}$), radiant temperature equal to $T_a$, and relative humidity of 20% (vapour pressure capped at 20 hPa for $T_a$>29°C). The final model output is determined by comparing the model human response to the reference conditions across the temperature range, and determining the offset from the reference (the UTCI final output value is the $T_a$ plus offset value, in °C).

*The* ***Wet Bulb Globe Thermometer (WBGT)*** index was created for the military in the 1950s (Yaglou and Minard, 1957). Currently it is the most widely used direct heat stress index for assessing possible exertional heat stress during low to high level physical activity (e.g. athletics, occupational safety, military).[26] The index integrates the influences of air temperature, humidity, radiant temperature, and wind speed, and applies a weighted average between the natural wet bulb temperature ($T_w$), dry bulb temperature ($T_a$), and globe temperature ($T_g$) as follows:

$$\mathrm{WBGT} = 0.7T_w + 0.2T_g + 0.1T_a \qquad [2]$$

Although historical limitations of the WBGT exist (e.g., applicability across climate types, misuse or non-use of all variables, misunderstanding of variables[51]), adhering to WBGT guidelines has helped many avoid exertional heat stress.

The **Thermal Work Limit (TWL)** is a rational heat stress prediction tool defined as the *"limiting (or maximum) sustainable metabolic rate that euhydrated, acclimatized individuals can maintain in a specific thermal environment, within a safe deep BCT (<38.2°C) and sweat rate (<1.2 kg hr$^{-1}$)".*[49] The TWL derives from the use of Equation (1) by setting the sum to equal the metabolic heat load (M) based on the established BCT and sweat rate limits provided above (thus the M = TWL at specified limits).

## 5. Conclusions

Human exposure to heat has emerged as a major public health concern, yet the term 'heat' is used rather loosely in the epidemiology of extreme heat literature. This primer has attempted to draw attention to the complexity of heat as a driver of health outcomes, and differentiated between the physical meaning of heat (i.e. '*energy contained within a substance*'), versus what the general public and those in public health or health-related fields perceive heat to be (i.e. 'high temperature'). Proper usage of the heat stress indices described here are dependent on the type of study and/or the application. Knowing how and why the indices were developed, and what variables are required, can help inform choice of the appropriate index for a given application.

This primer further draws attention to heat stress as an outcome of the synergistic effects of five main parameters affecting the human heat balance (HHB): high air temperature, humidity and ventilation levels, high radiation loads, and metabolic activity. The interaction of these parameters precipitates heat strain, whether manifest by increased sweat rates, a rise in body core or skin temperature, or a range of heat illnesses/injuries, including death.

Many challenges remain in assessing heat stress for health-relevant situations, whether indoor or outdoor and especially for particularly vulnerable groups. These include the measurement of heat stress variables at requisite temporal and spatial scales (e.g., personal versus population-level exposures to estimate the given effect), the choice of an appropriate empirical, direct or rational index for quantifying heat stress, and how heat strain can best be captured (i.e., physiological measurements). . In this regard, there is a 'time and place' for applying single meteorological variables or simple heat indices and the more complex HHB based models to the task of assessing heat stress. Accordingly, we conclude that models using such 'simple' measures like air temperature, or for example the temperature-humidity index, provide useful information for gauging the general population response to heat in an exposure-response manner with such measures serving effectively as a basis for providing heat warnings at the population (e.g. city) level. However, in the case of specific vulnerable populations, in situations that might put them at greater risk to heat exposure than the general population (e.g. people at mass gatherings, athletes, poorly designed dwellings and urban areas), knowing all the avenues of heat gain (e.g. source of radiative loads) and what comprises the heat load in terms of the individual components of heat is essential. Possessing this type of information, along with a person's metabolic rate and the current and evolving local/micro-level weather attributes, will help realise the potential of developing personal heat warning systems based on the HHB model and therefore achieve, in essence, a population to person scaling of the response to heat exposure.

Lastly it should be noted that the challenges outlined above are distinct from those of attributing all or part of an observed rise in mortality/morbidity to 'heat' during a heat event and how best to engender a public/individual response to warnings about impending health threatening high temperatures so as to avoid heat illness and death, especially amongst the vulnerable. These challenges fall broadly within the fields of epiclimatology and risk communication and point to the need for a holistic or cross-disciplinary approach to managing heat as a public health issue.

**Acknowledgements:**

We would like to thank David Hondula of Arizona State University for conversations regarding personal heat exposure during the writing of this manuscript, and Chris Orton at Durham University for drafting the figures.

**References:**


1. McGregor GR, Bessemoulin P, Ebi K, Menne B. Heat waves and health: Guidance on warning system development. 2010.
2. Meehl GA, Tebaldi C, Walton G, Easterling D, McDaniel L. Relative increase of record high maximum temperatures compared to record low minimum temperatures in the US. Geophys Res Lett. 2009;36(23).
3. Hope P, Wang G, Lim E, Hendon H, Arblaster J. What caused the record-breaking heat across Australia in October 2015? Bull Amer Met Soc,. 2016;97(12):S122 – 125.
4. Mitchell D, Heaviside C, Vardoulakis S, Huntingford C, Masato G, Guillod BP, et al. Attributing human mortality during extreme heat waves to anthropogenic climate change. Environ Res Lett. 2016;11(7):74006.
5. Takahashi C, Watanabe M, Shiogama H, Imada Y, Mori M. A persistent Japanese Heat Wave in Early Augus, 2015: Roles of Natural Variability and Human-Induced Warming. Bull Am Meteorol Soc. 2016;97:S107 – 111.
6. McGregor GR. Human biometeorology. Prog Phys Geogr. 2012;36(1):93–109.
7. Givoni B, Goldman RF. Predicting rectal temperature response to work, environment, and clothing. J Appl Physiol. 1972;32(6):812–22.
8. Ravanelli NM, Hodder SG, Havenith G, Jay O. Heart rate and body temperature responses to extreme heat and humidity with and without electric fans. Jama. 2015;313(7):724–5.
9. World Health Organization (WHO). Health factors Involved in working under conditions of heat stress: Technical Report 412. Geneva, Switzerland; 1969.
10. Armstrong L, Casa D, Millard-Stafford M, Moran D, Pyne S, Roberts W. American College of Sports Medicine position stand: exertional heat illness during training and competition. Med Sci Sport Exerc. 2007;39(556Y72).
11. Davis RE, McGregor GR, Enfield KB. Humidity: A review and primer on atmospheric moisture and human health. Environ Res. 2016;144:106–16.
12. Vanos J. Children’s health and vulnerability in outdoor microclimates: A comprehensive review. Environ Int. 2015;76:1–15.
13. Kenney WL, Craighead DH, Alexander LM. Heat waves, aging, and human

cardiovascular health. Med Sci Sports Exerc. 2014;46(10):1891.

14. Vanos JK, Warland JS, Kenny NA, Gillespie TJ. Review of the physiology of human thermal comfort while exercising in urban landscapes and implications for bioclimatic design. Int J Biometeorol. 2010;54(4):319–34.

15. Montieth J, Unsworth M. Principles of Environmental Biophysics. 3rd ed. Elsevier; 2008.

16. Driscol D. Human health. In: Houghton D, editor. Handbook of applied meteorology. New York: Wiley; 1985. p. 778–814.

17. Brown RD, Gillespie TJ. Estimating outdoor thermal comfort using a cylindrical radiation thermometer and an energy budget model. Int J Biometeorol. 1986;30(1):43–52.

18. Nielsen B, Strange S, Christensen NJ, Warberg J, Saltin B. Acute and adaptive responses in humans to exercise in a warm, humid environment. Pflügers Arch Eur J Physiol. 1997;434(1):49–56.

19. Coris EE, Ramirez AM, Van Durme DJ. Heat illness in athletes. Sport Med. 2004;34(1):9–16.

20. Shapiro Y, Pandolf K, Goldman R. Predicting sweat loss response to exercise, environment and clothing. Eur J Appl Physiol Occup Physiol [Internet]. 1982;48(1):83–96. Available from: http://dx.doi.org/10.1007/BF00421168

21. Moran DS, Pandolf KB, Shapiro Y, Laor A, Heled Y, Gonzalez RR. Evaluation of the environmental stress index for physiological variables. J Therm Biol. 2003;28(1):43–9.

22. Shapiro Y, Moran D, Epstein Y, Stroschein L, Pandolf KB. Validation and adjustment of the mathematical prediction model for human sweat rate responses to outdoor environmental conditions. Ergonomics. 1995;38(5):981–6.

23. Kuras E, Bernhard M, Calkins M, Ebi K, Hess J, Kintziger K, et al. Opportunities and Challenges for Personal Heat Exposure Research. Environ Health Perspect. 2017;

24. Vanos JK, Kalkstein LS, Sanford TJ. Detecting synoptic warming trends across the US Midwest and implications to human health and heat-related mortality. Int J Climatol. 2015;35(1):85–96.

25. Sheridan SC, Lee CC, Allen MJ, Kalkstein LS. Future heat vulnerability in California,

Part I: projecting future weather types and heat events. Clim Change. 2012;115(2):291–309.

26. Havenith G, Fiala D. Thermal Indices and Thermophysiological Modeling for Heat Stress. Compr Physiol. 2016;6.

27. Falk B, Dotan R. Children's thermoregulation during exercise in the heat-a revisit. Appl Physiol Nutr Metab. 2008;33(2):420–7.

28. Brotherhood JR. Heat stress and strain in exercise and sport. J Sci Med Sport. 2008;11(1):6–19.

29. Havenith G, Holmer I, Parsons KC. Personal factors in thermal comfort assessment: clothing properties and metabolic heat production. Energ Build. 2002;34(6):581–91.

30. Strath SJ, Swartz AM, Basset DR, O'Brien WL, King GA, Ainsworth BE. Evaluation of heart rate as a method for assessing moderate intensity physical activity. Med Sci Sport Exer. 2000;32(9):S465–70.

31. Epstein Y, Moran DS. Thermal comfort and the heat stress indices. Ind Health. 2006;44(3):388–98.

32. Brown RD, Gillespie TJ. Microclimate Landscape Design: Microclimatic Landscape Design: Creating Thermal Comfort and Energy Efficiency. NewYork.: John Wiley & Sons, Inc.; 1995.

33. Chen L, Yu B, Yang F, Mayer H. Intra-urban differences of mean radiant temperature in different urban settings in Shanghai and implications for heat stress under heat waves: A GIS-based approach. Energy Build. 2016;130:829–42.

34. Lindberg F, Grimmond CSB. The influence of vegetation and building morphology on shadow patterns and mean radiant temperatures in urban areas: model development and evaluation. Theor Appl Climatol. 2011;105(3–4):311–23.

35. Honjo T, Yamato H, Mikami T, Grimmond CSB. Network optimization for enhanced resilience of urban heat island measurements. Sustain Cities Soc. 2015;19:319–30.

36. Hu X-M, Xue M, Klein PM, Illston BG, Chen S. Analysis of urban effects in Oklahoma City using a dense surface observing network. J Appl Meteorol Climatol. 2016;55(3):723–41.

37. Muller CL, Chapman L, Grimmond CSB, Young DT, Cai X. Sensors and the city: a

review of urban meteorological networks. Int J Climatol. 2013;33(7):1585–600.

38. Tan J, Yang L, Grimmond CSB, Shi J, Gu W, Chang Y, et al. Urban integrated meteorological observations: practice and experience in Shanghai, China. Bull Am Meteorol Soc. 2015;96(1):85–102.

39. Best MJ, Grimmond CSB. Key conclusions of the first international urban land surface model comparison project. Bull Am Meteorol Soc. 2015;96(5):805–19.

40. Jenkins K, Hall J, Glenis V, Kilsby C, McCarthy M, Goodess C, et al. Probabilistic spatial risk assessment of heat impacts and adaptations for London. Clim Change. 2014;124(1–2):105–17.

41. Oke T. Initial guidance to obtain representative meteorological observations at urban sites. IOM Rep. 81, WMO/TD-No. 1250. 2006.

42. Johansson E, Thorsson S, Emmanuel R, Krüger E. Instruments and methods in outdoor thermal comfort studies–The need for standardization. Urban Clim. 2014;10:346–66.

43. Vanos JK, Warland JS, Gillespie TJ, Slater GA, Brown RD, Kenny NA. Human energy budget modeling in urban parks in Toronto, ON and applications to emergency heat stress preparedness. J Appl Meteorol Clim. 2012;51(9):1639–53.

44. Jendritzky G, Havenith G, Weihs P, Batchvarova E. Towards a universal thermal climate index (UTCI) for assessing the thermal environment of the human being. 2009.

45. Ketterer C, Matzarakis A. Human-biometeorological assessment of heat stress reduction by replanning measures in Stuttgart, Germany. Landsc Urban Plan. 2014;122:78–88.

46. Brown RD, Vanos JK, Kenny NA, Lenzholzer S. Designing Urban Parks That Ameliorate the Effects of Climate Change. Landcape Urban Plan. 2015;

47. Grundstein A, Knox J, Vanos JK, Cooper E, Casa DJ. American Football and Fatal Exertional Heat Stroke: A Case Study of Korey Stringer. Int J Biometeorol. 2017;

48. Epstein Y, Moran DS. Evaluation of the environmental stress index (ESI) for hot/dry and hot/wet climates. Ind Heal. 2006;44(3):399–403.

49. Brake DJ, Bates GP. Limiting metabolic rate (thermal work limit) as an index of

thermal stress. Appl Occup Environ Hyg. 2002;17(3):176–86.

50. Macpherson RK. The assessment of the thermal environment. A review. Br J Ind Med. 1962;19(3):151–64.

51. Budd GM. Wet-bulb globe temperature (WBGT) - its history and its limitations. J Sci Med Sport. 2008;11(1):20.

52. Parsons K. Human thermal environments: the effects of hot, moderate, and cold environments on human health, comfort, and performance. Crc Press; 2014.

53. de Freitas CR, Grigorieva EA. A comparison and appraisal of a comprehensive range of human thermal climate indices. Int J Biometeorol. 2016;1–26.

54. Steadman RG. The Assessment of Sultriness. Part I: A Temperature-Humidity Index Based on Human Physiology and Clothing Science. J Appl Meteorol. 1979;18:861–73.

55. Masterton JM, Richardson FA. Humidex: a method of quantifying human discomfort due to excessive heat and humidity. Downsview, Ontario: Environment Canada, Atmospheric Environment; 1979.

56. Rothfusz LP. The heat index “equation” (or more than you ever wanted to know about the heat index). NWS Technical Attachment SR 9023:2; 1990.

57. Bröde P, Fiala D, Błażejczyk K, Holmér I, Jendritzky G, Kampmann B, et al. Deriving the operational procedure for the Universal Thermal Climate Index (UTCI). Int J Biometeorol. 2012;56(3):481–94.

58. Yaglou CP, Minard D. Control of heat casualties at military training centers. AMA Arch Ind Heal. 1957;16(4):302.

59. Campbell GS, Norman JM. An Introduction to Environmental Biophysics. Second. New York: Springer; 1998.

60. ISO 7726. Ergonomics of the thermal environment -- Instruments for measuring physical quantities. Genva; 1998.

61. Kenny NA, Warland JS, Brown RD, Gillespie TJ. Estimating the radiation absorbed by a human. Int J Biometeorol. 2008 Jul;52(6):491–503.

62. Thorsson S, Lindberg F, Eliasson I, Holmer B. Different methods for estimating the mean radiant temperature in an outdoor urban setting. Int J Clim. 2007;27(14):1983–

93.

63. NOAA. NOAA's Watch, Warning, and Advisory Products for Extreme Heat. 2014.

64. Li PW, Chan ST. Application of a weather stress index for alerting the public to stressful weather in Hong Kong. Meteorol Appl. 2000;7(4):369–75.

65. Ramanathan NL, Belding HS. Physiological evaluation of the WBGT index for occupational heat stress. Am Ind Hyg Assoc J. 1973;34(9):375–83.

66. Sherwood SC, Huber M. An adaptability limit to climate change due to heat stress. Proc Natl Acad Sci. 2010;107(21):9552–5.

67. Matzarakis A, Mayer H, Iziomon MG. Applications of a universal thermal index: physiological equivalent temperature. Int J Biometeorol. 1999;43(2):76–84.

68. Vanos J, Warland J, Gillespie T, Kenny N. Thermal comfort modelling of body temperature and psychological variations of a human exercising in an outdoor environment. Int J Biometeorol. 56(1):21–32.

69. Blazejczyk K. New climatological-and-physiological model of the human heat balance outdoor (MENEX) and its applications in bioclimatological studies in different scales. Zesz IgiPZ PAN. 1994;28:27–58.

70. Belding HS, Hatch TF. Index for evaluating heat stress in terms of resulting physiological strain. Heat Pip Air Condit. 1955;27:129–36.

71. Gagge AP. An effective temperature scale based on a single model of human physiological temperature response. ASHRAE {T}ransactions. 1971;77:247–62.

72. Jendritzky G, de Dear R, Havenith G. UTCI-Why another thermal index? Int J Biometeorol. 2012;56(3):421–8.

73. Błazejczyk K, Jendritzky G, Bröde P, Fiala D, Havenith G, Epstein Y, et al. An introduction to the Universal thermal climate index (UTCI). Geogr Pol. 2013;86(1).

74. Steadman RG. A universal scale of apparent temperature. J Clim Appl Meteorol. 1984;23(12):1674–87.

75. Moran DS, Shitzer A, Pandolf KB. A physiological strain index to evaluate heat stress. Am J Physiol Regul Integr Comp Physiol. 1998;275(1):R129-134.

Table 1: Basic differences between heat and temperature

| | **Heat** | **Temperature** |
|---|---|---|
| Definition* | Heat is the energy contained within a substance. It represents the total energy of all the molecular motion (kinetic energy) in a substance or object. The hotter the substance or object the faster the molecular motion and the greater the heat contained within. | Temperature is a measure of the average heat or thermal energy of the molecules making up a substance or object. It is expressed by one of several arbitrary scales such as Celsius or Fahrenheit. How ‘hot’ or ‘cold’ a substance is dependent on how fast the atoms comprising that substance are moving. |
| Units | Joule | Celsius, Fahrenheit, Kelvin |
| SI Unit | Joule | Kelvin |
| Flow | Heat can be transferred or flow from one location to another if there is a difference in temperature (e.g., skin to air temperature). Heat flows are referred to as fluxes and measured in Watts (equivalent to 1 J/sec). In biometeorology and meteorology, heat flux densities are usually encountered in the literature - expressed as $W/m^2$ | Temperature does not flow, rather temperature differences or temperature gradients (e.g. $^{o}C/m$) determine the direction and magnitude of heat flow. Greater movement of heat *towards* the human body will therefore occur when the temperature difference between two objects (e.g., human body and environment) have a large temperature contrast. |
| Ability to do ‘work’ | Heat possesses the ability to do work | Temperature does not do work, rather it measures the degree of heat |

*The American Meteorological Society point out some of the confusion associated with heat as captured in its glossary entry for this term as follows: *“Heat, used as a noun, is confusing and controversial in its scientific meaning. The differential of heat is considered imperfect in that its value depends on the process applied. In the thermodynamic definitions in this glossary, heat is avoided as a noun or adjective except where required by established use. The process of heating is, however, defined as the net absorption of internal energy by a system.”* (http://glossary.ametsoc.org/wiki/Heat)

Table 2: General instruments used to monitor microclimate information for heat stress prediction. See Kuras et al.[23] for personal sensing technology of select variables.

| ***Variable*** | ***Instrument(s)*** | ***Modern Technology*** | ***Considerations*** |
|---|---|---|---|
| Air Temperature ($T_a$) (dry bulb temperature) | Thermometer ('of heat meter') | Mercury thermometer, tthermistors, thermocouples, bimetallic thermometer. | Relatively low cost. Ventilated radiation shield required. |
| Relative Humidity (RH) | Hygrometers ('water meter') | Psychrometer (wet-and-dry-bulb thermometer) Wet bulb has bulb wrapped in wet muslin with air flow moving over. Also measured based on changes in thermal conductivity of air due to vapour, or change in electrical resistance of (used by Kestrel WBGTs). | Ventilation important, as is the simultaneous accurate measurement of $T_a$. Thus, RH and $T_a$ often measured together. RH is rarely the correct value to use in public health and epidemiological studies, and can be converted to proper, independent parameters (see Davis et al.[11]). |
| Longwave (LW) Radiation | Pyrgeometer ('fire-earth meter') | "Thermal": Silicon dome (transmits infrared only), black disk heats up proportional to LW radiation. | Often high-cost and complex. Calibrations required. Low-cost option for outgoing LW is to obtain a surface temperature and apply Boltzmann's law.[59] |
| Shortwave (SW) Radiation | Pyranometer ('fire meter') | "Thermal": Glass dome with black disk changing temperature proportional to SW radiation, producing a voltage output (e.g., Kipp & Zonen) "Photocell": converts specific wavelengths of light into electrical energy (Li-COR). | Thermal: often high cost and complex. Photocell: less expensive and less complex, but only valid under 'open sky' conditions. Calibrations required for both. Portable and less complex options are made by Huskeflux. |
| Net Radiation (NR) | Net Radiometer (upward and downward pyranometer and pyrgeometer) | Use pyranometer and pyrgemoeter technologies (e.g., Kipp & Zonen CNR4). | Expensive, calibrations required, more complex. |
| Wind speed and direction | Anemometer ('wind meter') | Cups or propeller: rotate proportional to wind speed. Direction obtained through the use of a wind vein. Hot wire anemometers: wind cools wire proportionate to speed. | Height of measurement is crucial. Most windspeed measurement come from 10m height, which can be brought to human height with log-wind equations. |
| Radiant Temperature | Globe thermometer,[60] cylindrical radiation thermometer,[61] grey globe thermometer;[62]<br><br>3D or related models integrating SW and LW radiation.[42] | Temperature sensor, such as thermistor or thermocouple, embedded in hallow globes or in conductive material (e.g. epoxy) to transfer both sensible and radiant heat to temperature sensor.<br><br>Net radiometers are required for 3D setup. | Slow response time of larger sensors is an issue;[51] colour and shape inaccuracies for representing a human.<br><br>Very costly to have three net radiometers. |

Table 3: Common heat indices used in research and practice world-wide. Rational indices are utilized within research, while direct and empirical are used more in practice and by the public.

| **Index** | **Type & Main Inputs[a]** | **Scale/Units** | **Main application(s) & notes** |
|---|---|---|---|
| Simplified Heat Budget Models (Direct & Empirical) | | | |
| Heat Index | Direct index, yet empirically derived in its conception.[54] $T_a$, RH. | °F | Heat wave warnings and guidance, USA.[63] Full population; relative thresholds for vulnerable. |
| Humidex | Direct index, yet empirically derived. $T_a$, VP | °C | Heat wave warning and guidance, Canada.[55] Full population; relative thresholds for vulnerable. |
| Net Effective Temperature (NET) | Direct. $T_a$, RH, V | °C | Heat wave warning and guidance, China.[64] |
| Wet Bulb Globe Thermometer (WBGT) | Direct. $T_w$, $T_a$, $T_g$ | °F / °C | Exertional heat stress & illness; military, athletes, active populations, occupational heat exposure.[58,65] |
| Wet bulb temperature ($T_w$) | Direct. $T_w$. | °F / °C | Classic heat illness; $T_w$ > 35°C cited as limits of habitability for human adaptation to heat.[66] No set warnings thresholds for general population. |
| Complex Heat Budget Models (Rational) | | | |
| Physiological Equivalent Temperature (PET) | Rational. $T_a$, $T_{mrt}$, RH, V, $M_{act}$ | °C | Thermal comfort, urban design.[67] Applied to general population. |
| COMfort FormulA (COMFA)/COMFA* | Rational. $T_a$, NR, VP, V, $M_{act}$, $I_{cl}$. Utilizes Eq. 1. | W $m^{-2}$ | Thermal comfort, urban design, heat stress prediction sedentary/active (COMFA*).[17,68] Applied to general population; can be age-specific. |
| Man-ENvironment heat EXchange model (MENEX) | Rational. $T_a$, NR, RH, V, $M_{act}$, $I_{cl}$. Utilizes Eq. 1. | W $m^{-2}$ | Thermal comfort, urban design, heat stress during exercise.[69] |
| Heat Stress Index (HSI) | Rational. VP, $T_a$, V, $M_{act}$. Ratio of required to maximum evaporation. | Scale from 0–100 (HSI = $E_{req}/E_{max}$) | Heat stress prediction, classic and exertional.[70] General population. |
| Standard Effective Temperature (SET) | Rational. $T_a$, $T_{mrt}$, RH, V, $M_{act}$, $I_{cl}$. Utilizes Eq. 1. | °C | Two-node method, represents skin temperature and wettedness.[71] |
| Thermal Work Limit (TWL) | Rational. $T_a$, NR, VP, V. | W $m^{-2}$ or METs | Occupational and exertional heat stress.[49] |
| Universal Thermal Comfort Index (UTCI) | Rational. $T_a$, $T_{mrt}$, RH, V, $M_{act}$, $I_{cl}$ | °C | Physiologically-based thermal comfort.[26,72,73] |
| Apparent Temperature | Rational. $T_a$, $T_{mrt}$, RH, V, $M_{act}$, $I_{cl}$ | °C | Assessment of hot/humid weather; thermal comfort; clothing.[54,74] |
| **Other** | | | |
| Physiological Strain Index (PSI) | Empirical. Requires physiological inputs of heart rate and BCT. | Strain (0–10) | Clinical studies, exercise/active individuals.[75] |
| Environmental Stress Index (ESI) | Empirical. SR, RH, $T_a$ | °C | Exercise (athletic, military, occupational).[21] |

| | | | |
|---|---|---|---|
| Discomfort Index (DI) | $T_w$, $T_a$ | °F | Human (dis)comfort required for air conditioning for sedentary individuals. |

[a]*air temperature ($T_a$), relative humidity (RH), vapour pressure (VP), windspeed/ventilation (V), mean radiant temperature ($T_{mrt}$), net radiation (NR), clothing insulation ($I_{cl}$), metabolic activity ($M_{act}$), solar radiation (SR).*

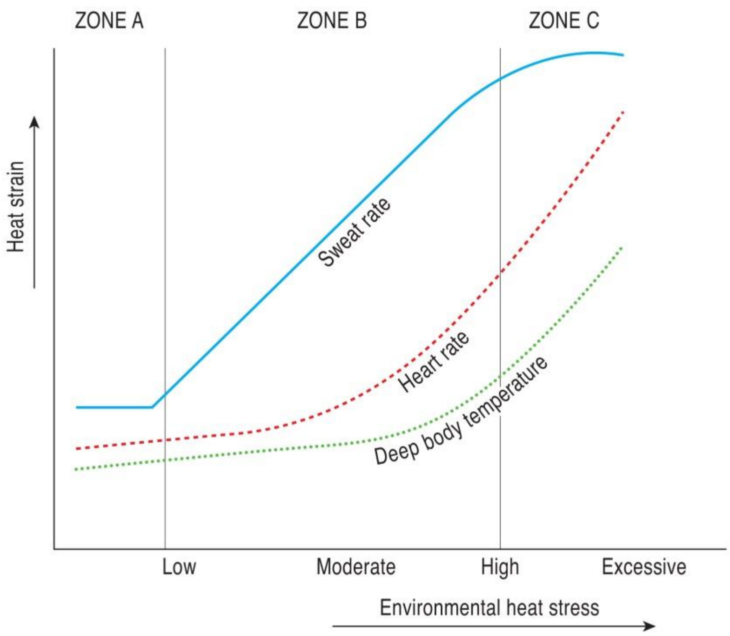


Figure 1: Conceptual diagram of heat strain related to heat stress (body core temperature, sweat rate, heart rate) arising from environmental heat loads (horizontal axis). Zone A: No heat stress; Zone B: Increasing heat producing strain in terms of sweat loss, BCT largely not affected but strain noticeable via increasing heart rate; Zone C: Increasing heat stress with sweat loss approaching a maximum. Rapidly increasing strain evident manifest in rapidly increasing heart rate and BCT. Adapted from WHO.[9]

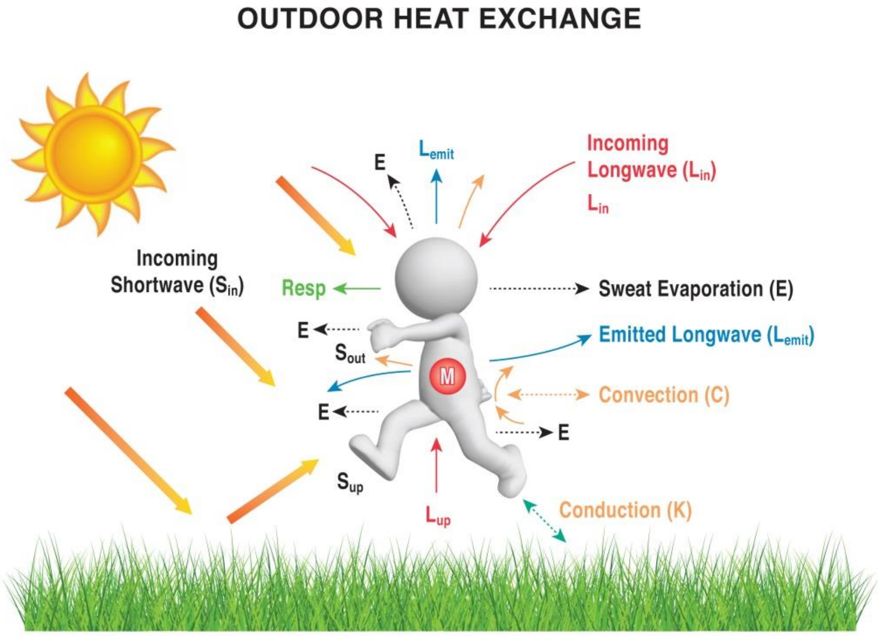


Figure 2: Heat exchange between the environment and human body in an outdoor environment. In normal conditions, a human's energy balance will increase due to metabolic heat generation (M) and radiation in the form of shortwave ($S_{in}$ and $S_{up}$) and longwave ($L_{in}$ and $L_{up}$) from the sky and ground. A human will normally lose heat through convection (C), evaporation (E), emitted longwave radiation ($L_{emit}$), and respiration (Resp).