Computational models of human response to urban heat

From physiology to behaviour

Melnikov, V.

Publication date
2021

Chapter 1

Introduction

1.1 Motivation

The epigraph I start my thesis with is the first line of *The Little Golden Calf* – a satiric novel about life in Soviet Union published in 1931. Though joking, authors emphasise an important trend of that epoch: pedestrians being forced out of the streets of the cities by the booming use of automobiles. *"Pedestrians comprise the larger part of humanity. More than that: its better part. Pedestrians created the world. It was they who built cities..."* state the authors to underline the paradox of the process: those who have built cities, for comfort of whom cities are intended, are degraded to second-class citizens and *"lead martyr's lives in the big city"*[1].

90 years have passed since the book was published, the urban population of the world has rocketed more than tenfold (from an estimated 0.33 to 4.35 billion living in an urban environment) [1, 2, 3]. With the growth of cities, the number of cars is constantly growing [4]. To complicate things further, it is not only cars, but the whole spectrum of urban stressors, such as crowding [5], pollution [6], noise [7] and climate [8], which are omnipresent in modern cities. The problem of big cities pinpointed almost a century ago was not solved, rather, it was exacerbated.

In fact, the pedestrian behaviour, expressed in attendance of outdoor space, walking rates and walking speeds, was found to be directly associated with the level of crowding, noise [9], properties of urban form [10, 11] and climate [12, 13]. Correlation between average walking speeds in the city and its size

[1] Here and before the translation of *The Little Golden Calf* from the Russian by Anne O. Fisher is used.

[14] has become one of the urban scaling laws [15] and elevated average walking speed was not only suggested to be an indicator of pace-of-life in the city [16], but also hypothesised as withdrawal behaviour from over-stimulating outdoor urban environments [14]. Stressful urban environments are not just a matter of reduced walking, but a matter of everyday comfort, health and well-being of billions of people [17]. The key to enhancement of experience and lives of urban dwellers is understanding the complex interaction of people with urban environments, of people's response to urban stimuli on all levels and scales. This problem is drawing growing attention across the globe, leading to multi-million dollar research initiatives [18, 19, 20].

Outdoor thermal comfort (OTC) – a result of complex interaction of people and outdoor thermal environments has seen increased research attention in the last decades. With studies spanning Asia [21, 22] and Europe [23, 24, 25], North [26, 27] and South [28] America, Africa [29, 30] and Australia [31], OTC can be called a global concern. This is due to the global processes of climate change [32], urban heat islands (UHI) [33] and rapid urbanisation [34], which result in more people being exposed to excessive urban heat, challenging many aspects of modern society: public health [35], human [36] and economic development [37], mental health [38] and social relations [39].

The current OTC research focuses on understanding the interaction of climate and urban physical environment, to reduce, through design and planning, the amount of excessive heat people are exposed to [40, 41, 42, 43]. This allows for testing and implementation of urban heat mitigation strategies, such as orientation and materials of buildings [44], built [45, 46] and green infrastructure [47, 48, 49] and smart path planning [50, 51]. However, human response to thermal environments, while being an ultimate focus of OTC, is not yet understood in its entirety. Existing OTC studies are usually limited to measurement of subjective sensation and perception through surveys regressing them to properties of thermal environments.

It is the complexity of human response to thermal environments [52] that renders the task of comprehensive understanding of this response a non-trivial one. Humans and their thermal environment form a complex system, with intricate interaction on multiple levels and non-linear dynamics. This thesis targets at understanding this complex response of humans to their thermal environments through experiments, mathematical modelling and computer simulation. We address the complexity of the problem by decomposing the overall response into different levels (namely physiological, perceptual and behavioural response to urban heat). Based on the existing body of knowledge and our own empirical studies, for each of these levels of human response we propose dedicated models. These computational models enable us to achieve the ultimate goal of this research: to develop an understanding of the complex connection between the urban climate and the human thermoregulatory system and how this in turn triggers adaptive response in humans. The resulting work provides novel computational tools and methods to study the interaction of the human thermoregulatory response and other processes within the human body. We demonstrate the application of these tools to infer the heat stress cost of elevated walking speeds and the regimes of heat exposure and physical activities, which can have a detrimental effect on the performance of the human innate immune system response.

The studies reported in this thesis pave the way towards thinking of outdoor thermal comfort in its most explicit, precise and insightful way: as a result of complex response of humans to dynamic thermal environments on multiple levels from physiology to behaviour.

1.2 The context of this thesis

1.2.1 Current state of the research

Urban climates are produced by a combination of the climate and the built environment as depicted in Figure 1.1. We emphasise the role of the built urban environment in shaping the urban climate. Ultimately, the way human settlements are designed, planned and operated determines both the urban climate and the resulting microclimate people experience on an every-day basis. The phenomenon of outdoor thermal comfort arises as a result of the interaction of people and their microclimate. This interaction can occur at multiple levels:

through a physiological response, a change in perception or a behavioural response. This thesis develops computational methods and tools to help understand how these responses occur and how they help regulate outdoor thermal comfort (see Figure 1.1). In the following subsections we describe the current state of the art research related to urban climate and outdoor thermal comfort modelling, motivate the need to focus on human response to thermal environments and briefly discuss the levels at which we consider this response.

FIGURE 1.1: Conceptual diagram of the OTC process, the levels of human response to thermal environments and interaction with outer environmental domains.

Urban climate

Climate is the first component of the complex phenomenon of outdoor thermal experience of people. Climate, and adaptation to it, have shaped, without exaggeration, the way humanity has developed. The way our ancestors populated the land [53], the food we eat [54] and clothes we wear [55, 56], the houses we live in [57] and activities we perform [12] – this all is at least partially affected by the climate we live in.

The relation between climate and humanity is not a one-way process, the way we live and perform our activities is now shaping the climate. The process of global climate change [32], characterised by rising temperatures in many parts of the world, has its anthropogenic input [58]. And while it is a matter of ongoing public debates, to what extent climate change is of anthropogenic nature [59], there is no doubt in the nature of notoriously known Urban Heat Island (UHI) effect [60]. UHIs are defined as a difference between air temperatures in urban core and rural surroundings of cities [33], and are due to the intrinsic properties of modern cities: capturing of heat due to increased heat capacity of building materials, anthropogenic heat emission from manufacturing, transportation and indoor air conditioning, obstruction of wind flows and other factors [61].

In fact, if there is anthropogenic input in climate change, then cities and activities in them are the main contributors of it [62]. It was found, however, that parameters of cities such as city size, green cover and albedo of materials are associated with the intensity of UHI [63]. This implies that certain urban planning and policy measures taken on a local scale can reduce the UHI and improve the thermal experience of people in outdoor environments.

To inform climate-aware policy making, urban climate modelling is used. The models range from macro- and meso-scale (such as Weather Research and Forecasting model with a grid resolution from kilometers up to 30 meters [64]) to microscale models, such as EnviMet [65] with resolution of up to 0.5 meters. Being computationally expensive, the models have to compromise either scale, or resolution, or the number of simulated parameters. Specialised models are developed to, for example, simulate the radiative heat in an urban areas [66, 67], effect of heat rejection from the air conditioning systems [68] and effect of trees on street-level cooling [43].

While having some limitations, the models of urban climate are constantly developing. With the growing computational power, it is reasonable to expect that eventually we will develop models capable of comprehensive simulation of the microclimate with a resolution on the scale of building blocks and neighborhoods if not cities. We argue, however, that while being critically important, climate simulation by itself does not answer the question of how people will experience climate and importantly what will be their response to it. For these questions to be answered, human response to outdoor thermal environments should be understood and explicitly modeled.

Outdoor thermal comfort

Outdoor thermal comfort (OTC) is the broad term encompassing human response to outdoor thermal environments. OTC research has developed from indoor thermal comfort studies, which were critical to provide comfortable working and living environments for occupants of buildings [69]. The measures of indoor climate such as predicted mean vote (PMV) and predicted percentage of dissatisfied (PPD) [70] were developed to measure the comfort of thermal environments. The thermally neutral indoor environments usually correspond to level of PPD = 5%, which increases as the environment diverges from thermal neutrality. The guidelines for indoor air conditioning systems usually focus on air temperature and relative humidity, under the reasonable assumption that radiation and air velocity are kept low and relatively constant in enclosed indoor environments.

Outdoor environments, however, are more heterogeneous. There radiation and windchill play an important role. Oftentimes, thermal parameters of outdoor environments interact in a complex manner by compensating or amplifying the effect of one another on thermal regulation. To account for that, physiological indices of microclimate are used. Out of them, physiologically equivalent temperature (PET)[71] and universal thermal comfort index (UTCI) [72] are probably the most widely used. These indices measure microclimates by their effect on the thermal state of the human body. Reducing multiple environmental and personal parameters to one number, they allow for comparison between multiple microclimates in terms of their impact on the thermophysiological state of the human body. The index value, defined in degrees Celsius, corresponds to air temperature in reference indoor environment required to achieve the same steady thermophysiological state as is achieved in the assessed microclimate. This value of an index can be calculated using multiple tools [66, 67], including the micro-scale climate modelling tool EnviMet [65], which allows one to assess simulated microclimate scenarios in terms of a persons physiological response to them.

The high variability in microclimate parameters in outdoor environments is complemented by high temporal variation of outdoor climate due to its own nature and the nature of human activities in it. Thus, a stable thermophysiological state is almost never achieved in outdoor environments [69]. What is perceived as pleasurable exposure after exiting an air conditioned building can be felt and perceived as stressful by a person, who has already spent considerable time outdoors or is dressed in heavy clothing. Moreover, human activities are not evenly distributed in the outdoor urban spaces and are of a different nature (e.g. transit or leisure). This implies, that modelling space use and human behaviour is important to understand exposure and evaluate the impact of environment on people, who use it. The need for a more comprehensive approach to modelling of OTC was emphasised in a paper dating 2012 [73]. In it, the authors propose an agent-based approach and multi-level modelling of an individuals' response to thermal environments. Since then, several studies have advanced this avenue of research [74, 75, 76], but there is still a need for the development of a comprehensive set of models on all levels of human response to microclimate. The studies of this thesis bring us closer to this goal.

1.2.2 People in thermal environments

Human response to thermal environments (outdoor thermal comfort) is a complex multi-level phenomenon. Figure 1.1 depicts outdoor thermal comfort process showing the levels of response considered within this thesis: physiology, perception and behaviour. We aim at gaining a better understanding of the response on these levels through the creation of a set of computational models. The following subsections will describe the fundamentals of human response on the three levels depicted in Figure 1.1 to motivate their importance, while deeper insights will be given in the separate chapters of this manuscript.

Physiological response: thermal regulation

The human body constantly interacts with its environment, in thermal terms the body can be considered a sink or a source of energy dissipated to or gained from the environment. Heat exchange between the body and its thermal environment is happening by convection, radiation, respiration and evaporation [77]. Additionally, part of internal metabolic energy production is spent on mechanical work (e.g. moving the center of mass and limbs in walking) [78]. These processes are graphically presented in Figure 1.2.

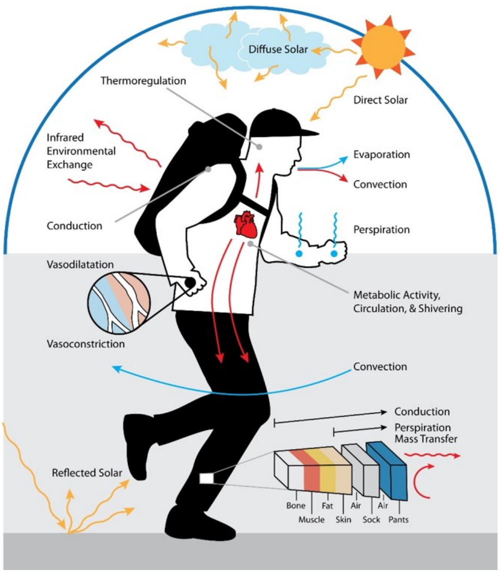

FIGURE 1.2: The process, components and parameters of thermal regulation of human body and heat exchange between it and the surrounding environment. Reproduced from: https://www.thermoanalytics.com/

The goal of the thermoregulatory system is to maintain this heat exchange in balance with the internal heat production to ensure the core temperature remains close to set temperature of 36.8°C vital for proper functioning of biological processes of a human body. Thermoregulatory system employs autonomous mechanisms such as vaso- dilation and constriction, shivering and sweating to maintain core temperature close to the set point of 36.8°C [77]. This system is sensitive to even small deviations of core and skin temperature from the set point, resulting in a thermal sensation (on a scale from cold to hot) that will drive human response on the higher levels of adaptation to thermal environment (discussed in the following subsections).

Failing to maintain heat balance, due to the limited capacity of a thermoregulatory system, results in hypo- or hyperthermia. Prolonged exposure to these conditions has detrimental effects on human health [79] and can be lethal [80]. While being a sophisticated first response to heat stress, the physiological system of thermal regulation has its limits and the adaptation and response at higher levels is crucial for efficient thermal regulation.

Multiple models of the human thermoregulatory system exist [81]. Most differ in terms of the granularity of body parts and the layers of body tissue considered [82, 83]. In Chapter 2 we describe, using a system dynamics representation, an enhanced version of a classical two-node model and compare it to the performance of other existing models. This model serves a corner stone for the subsequent studies of this thesis, due to the fact that the physiological state of the human body is the main driver of human response at all levels.

Psychological response: thermal perception

Human psychological perception is the next level on which thermal sensation is felt and is typically evaluated on the scale comfortable-to-uncomfortable [84] or acceptable-to-unacceptable. This mapping might appear straightforward, but as will be shown later, it is as complex as any perceptual process in humans. Remarkably, humans are probably the only animals that voluntarily compromise their thermal regulation to a life-threatening extent for other, non-vital, purposes such as religion and fun [85]. The role of perception in this behaviour is pivotal.

In a study of outdoor thermal comfort in Cambridge, UK the predicted percentage of dissatisfied people (see Section 1.2.1) was calculated for a set of observed microclimatic conditions [86]. Occupants of a public space were asked to give their evaluation of the thermal environment. The observed percentage of dissatisfied people was dramatically lower than expected (13% observed vs. 91% predicted). It turned out that, having been developed for indoor environment, PMV and PPD indices are not able to predict thermal satisfaction in outdoor environments. Factors such as perceived control, naturalness, expectations and past experiences should be considered, when predicting perception of the thermal environment [87]. While gaining more insights into factors influencing human thermal perception, *"Yet in the case of thermoregulatory behaviour, the interface between physiology and psychology remains largely terra incognita"*, Cabanac (2010) [85].

The myriad of existing studies of OTC resorts to measurement of perception of thermal environment through surveys and questionnaires [88]. Measuring the thermal environment and calculating physiological indices of microclimate (see Section 1.2.1) allows to map thermal conditions to average perception. This mapping is not universal, the same values of physiological index are perceived differently in different parts of the world, which makes it necessary to recalibrate the perception scale for particular regions [89]. Even within the same city, these scales are adjusted for land use (residential, natural, etc.), type of activity (leisure, work, commute) and age group [90]. These hardly generalisable developments, while being of practical value for local policy and planning, unfortunately add little to common understanding of climate perception.

Motivated by the discussed complexity of the perception process and little existing knowledge, we do not approach development of computational models of microclimate perception. Our approach rather relies on the locally calibrated mapping of values of physiological index (and thus physiological state in given climate) to average perception. This estimated level of perception will then serve as an interface between physiological and behavioural models.

To tackle this issue of environmental conditions and perception, part of the research of this thesis involves a real-world experiment on pedestrian behaviour in outdoor environments. The data collected within the behavioural experiment presents a unique combination of precise measurement of climate, exposure, physiology, perception and behaviour. We discuss its potential to advance the understanding of thermal perception in conclusions to this thesis.

Behavioural response: thermoregulatory behaviour

In Section 1.2.1 we have discussed the different ways climate has shaped humanity. All the examples of adaptation to climate are nothing but thermoregulatory behavioural response of people. As alluded to in Section 1.2.2, autonomous (physiological) response to thermal environment is limited and behavioural adaptation is the only means of thermal regulation in the long run [91]. Understanding this behaviour is critical to assess, predict and improve the experience of people in outdoor thermal environments.

Behavioural responses can be classified as either reactive (adaption *to* environment) or proactive (adaptation *of* environment) [86]. In this thesis we focus on the former. The latter is considered outside the scope of our research. In animal and human behaviour, postural, activity and displacement behavioural adaptations to thermal stimulation are probably the most pronounced [85].

The empirical studies of activity intensity adaptation and displacement response in outdoor thermal environments are reported in the two chapters of this manuscript. The intensity of activity determines the rate of internal heat production. Thus, by adjusting activity intensity one can minimise heat stress [92]. It was previously shown in laboratory studies that people are capable of efficiently avoiding both hypo- and hyperthermia through regulation of activity [93]. We investigate the presence of this adaptation to the natural outdoor thermal environments in the context of urban pace of life (see Section 1.1) in Chapter 4. When exposed to a thermal gradient in laboratory environments, animals move to a location with a more comfortable temperature, a process called thermopreferendum [85]. In Chapter 5 we study this behaviour in people in natural environments to quantitatively investigate the additional perceived effort of walking under the sun.

While there are existing studies of thermal behaviour in outdoor spaces, they mostly observe the outcome of this behaviour at an aggregate level (e.g. clothing level [55, 56] or attendance and activities in public spaces [12] or walking rates [13]). Our studies, however, investigate momentary behavioural response of individuals to dynamic thermal environment, providing a new perspective on human thermal behaviour in natural environments.

1.3 Outline of this thesis

This thesis is composed of five studies performed in the concept of multi-level human response to thermal environment presented in Figure 1.1. Each of these chapters is based on the manuscripts published in or submitted to peer-reviewed proceedings and journals. Below we describe how these chapters come together and constitute the achievement of the goal of current thesis: building a comprehensive understanding of multi-level response of people to dynamic thermal environments.

Chapter 2 describes the model of a physiological response to thermal environments. It provides the full definition of the classical two-node model of human body thermal regulation. We do it with a system dynamics approach: mapping out all the components in stocks-and-flows diagram allows for understanding of complex causal relations and feedback loops in interaction of body energy stocks and parameters with environment. We validate the model on available data on dynamic response of core and skin temperature and propose adjustments to model parameters which significantly improve the accuracy of predicted dynamics of the thermoregulatory system, attaining comparable or even better accuracy than more sophisticated models. This combination of high accuracy in dynamic scenarios and relatively low computational complexity makes the model a good candidate for use in agent-based modelling of OTC. This model is used in our later studies and provides a reliable and comprehensive representation of thermophysiological response to a wide range of thermal environments.

In Chapter 3 we describe the state-of-the-art of pedestrian behaviour modelling in the context of response to dynamic environments. This study proposes the proxy to perceptional response to thermal environment. Behavioural models are formulated as functions of deviation of an instantaneous value of a physiological index (such as PET, which can be calculated with a physiological model described in Chapter 2) from the acceptable range. We hypothesise four different behaviours and formulate the models for them. Two of these behaviours, namely speed adaptation and adaptive path choice, have become the focus of two consequent studies, reported in Chapters 4 and 5. The agent-based modelling approach to pedestrian behaviour as a process of human interaction with physical and thermal environment on several levels constitutes the practical guide to implementation of human-centered simulation of OTC.

We investigate the walking speed adaptation as behavioural thermoregulatory response to thermal environments in Chapter 4. Based on existing literature and physiological underpinnings of thermal regulation, we hypothesise that walkers alter their walking speed to adjust the rate of metabolic heat production and to improve their thermal comfort. We have performed this study in the context of elevated urban pace of life – a counteracting motive of walking speed behaviour. We use physiological model to formulate the heat-stress-optimal walking speed and calculate its values for a broad range of thermal environments. We test the predicted values of heat-stress-optimal walking speeds against those empirically observed in a natural experiment in Singapore. We find that the values of average walking speed are systematically higher than heat-stress-optimal speed. We then analyse the implication of elevated walking speeds on additional heat stress due to pace of life in Singapore. The experiment in this study investigated the behavioural response to different shaded thermal environments (i.e. having no apparent visual and radiative stimulation), the behaviour under pronounced presence of the sun has become a focus of the Chapter 5.

Chapter 5 presents the results of investigation of path choice behaviour of people in stressful outdoor environments. We describe the design of experiment with human participants in natural outdoor environment, which is in contrast to reported human behaviour studies performed in lab environments. Observing people taking longer, but less sunny paths, allowed us to measure the burden or effort associated with walking under the stressful exposure to the sun. We use video recordings and computational models of a space and sun movement to precisely characterise, in terms of sun-shade composition, the path options provided to participants. This allows us to quantitatively estimate a distance-inflating coefficient of the sun – a proxy to associated effort of walking under the sun. The results provide quantitative understanding of human perception of the effort of walking under the sun, tree shade and building shade and its implications for the path choices one might expect to observe in urban environments.

While in the first four chapters the reader is guided through the three levels of human response to thermal environments and the proposed models for them, Chapter 6 demonstrates the use of these models to address important questions beyond thermal comfort. We first investigate through computational modelling the performance of the human innate immune system (HIIS) under the elevated core temperatures. We estimate the range of core temperatures, at which the performance of the HIIS is compromised. We employ a physiological model of human thermal regulation to identify heat exposure and exercise intensity regimes, which causes body core temperatures to reach a level undermining the performance of the HIIS response. Our study demonstrates that, apart from apparent thermal discomfort, heat stress affects the basic biological mechanisms of human body beyond thermal regulation, and behavioural thermoregulatory response is crucial to preserve the proper functioning of these vital systems of human body.

Chapter 7 concludes the contribution of this research and discusses the directions for its further development and integration into agent-based OTC simulation framework.