Humboldt-Universität zu Berlin

Dissertation

Urban Climate and Heat Stress Hazards – an Indoor Perspective

Zur Erlangung des akademischen Grades doctor rerum naturalium (Dr. rer. nat.) im Fach Geographie

Mathematisch-Naturwissenschaftliche Fakultät

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Datum der Einreichung: 29.05.2017

Datum der Promotion: 14.08.2017

ACKNOWLEDGEMENTS

First of all and foremost I would like to thank my supervisor Prof. Dr. Wilfried Endlicher for his support during the whole process of this work. Thank you for the opportunity to be a part of the research project and your trust in my skills. Furthermore I have to thank the reviewers Prof. Dr. Christoph Schneider and Prof. Dr. Dieter Scherer for their expertise and time they spend on this thesis.

Thanks to the German Research Foundation (DFG) for funding this work within the DFG research unit 1736 UCaHS (Urban Climate and Heat Stress in mid-latitude cities in view of climate change).

Dr. Marcel Langner from the Federal Environment Office (UBA) and former co-worker, who guided me to the first month of the project by sharing his knowledge about the establishment of an indoor monitoring network. Thank you for your advice and support choosing the appropriate measurement equipment.

My colleagues in the DFG program UCaHS in specific Prof. Dr. Dieter Scherer, Dr. Ute Fehrenbach, Dr. Fred Meier, Britta Jänicke and Katharina Mucha, without their help this thesis would never have been possible. Thank you so much for all the meetings, workshops and encouraging discussions.

My co-workers from the Chair of Climatology, Dr. Katharina Scherber, Dr. Reinhardt Kleßen, Klaus Hartman and Sylvia Zinke-Friedrich have supported me with words and deeds and created a great working environment. A special thanks to my former co-worker Dr. Katrin Burkart, who supported me with her knowledge and accompanied me through my third journal article. Thanks to Philip Schuster for his assistance in data collecting.

Finally, I owe a great debt of thanks to my Family. Without the emotional and financial support of my parents I would have never been able to finish my study as I did. I am particularly grateful to Silvio, who encouraged and always listened to me in hard times and above all supported me by being a wonderful father to our daughter Frida.

ABSTRACT

Heat stress influences not only the comfort of humans but also human health. Due to the projected consequences of climate change, research on the impacts and general characteristics of heat periods has increased in recent years. Urban agglomerations have been a particular focus of these studies due to higher air temperatures and hence increased thermal strain compared to rural surroundings. Heat stress in outdoor environments has been investigated extensively, whereas only a few studies have focused on indoor environments. People in industrialized countries spend approximately 90 % of their day in confined spaces and hence are mainly exposed to indoor climate. Analyses of indoor climatic conditions are essential to understanding the underlying processes, determining the impacts on humans and developing appropriate adaptation measures.

The aim of this work is to investigate and assess different indoor climates and provide a valuable contribution to future research questions. To analyze indoor climate characteristics or, rather, the influence of different meteorological parameters, the indoor climate in four rooms in one building without user behavior was measured and examined. The results were used to establish a detailed indoor measurement system at different study sites distributed over Berlin. Air temperature, mean radiant temperature, relative humidity and air velocity were continuously measured in 31 rooms in eight buildings from summer 2013 until summer 2015. The gathered data were then used to assess indoor heat stress variability on a temporal and spatial scale using the UTCI (Universal Thermal Climate Index). Furthermore, outdoor data from façade measurements were used to examine the influence of outdoor climate as a driving factor of indoor climate. Finally, an extensive analysis of the influence of indoor climate and outdoor climate on mortality was conducted by applying generalized additive models (GAM).

The results indicate that indoor heat stress is a severe threat. All study rooms experienced high thermal loads, regardless of the building type they were located in or their location within the building. Indoor UTCI values varied up to 6.6 K within the city and up to 7 K within buildings and further exhibited very high heat stress levels during night compared to outdoors. The highest values were measured in modern buildings with a high percentage of windows. Among the different driving factors of indoor climate, outdoor climate was confirmed to have the highest impact. Moreover, this thesis shows that indoor air temperature is an equally good predictor of mortality compared to outdoor climate. Given the increasing trend of urbanization and the aging of the population it is likely that adverse heat effects will become more prevalent within in the coming decades. Additionally, increasing temperatures due to global warming may aggravate the situation.

ZUSAMMENFASSUNG

Hitzestress beeinflusst nicht nur das Wohlbefinden, sondern vor allem auch die menschliche Gesundheit. Die prognostizierten Folgen des Klimawandels führten deshalb innerhalb der letzten Jahre zu einer Zunahme an Studien, welche sich mit den Auswirkungen aber auch den Charakteristika von Hitzeperioden befassten. Dabei standen hauptsächlich städtische Agglomerationen im Vordergrund, da diese durch höhere Temperaturen im Vergleich zum Umland eine zusätzliche Belastung aufweisen. Während Hitzestress im Außenraum bereits detailliert untersucht wurde, gibt es aktuell nur sehr wenige Studien, welche sich mit thermischen Belastungen im Innenraum befassen. Dabei hält sich die Bevölkerung der Industriestaaten im Durchschnitt durchschnittlich 90 % des Tages im Innenraum auf und ist demzufolge hauptsächlich dem Innenraumklima ausgesetzt. Analysen der klimatischen Bedingungen im Innenraum sind essenziell, um zugrundeliegende Prozesse zu verstehen, die Auswirkungen auf den Menschen zu erfassen und passende Anpassungsstrategien entwickeln zu können.

Ziel der Arbeit ist es daher, verschiedene Innenraumklimata zu untersuchen und zu bewerten und dadurch einen Beitrag für künftig auftretende Fragestellungen zu leisten. Zur Untersuchung der Charakteristika eines Innenraumklimas bzw. dem Einfluss der unterschiedlichen meteorologischen Parameter, wurden 4 Räume ohne Nutzerverhalten innerhalb eines Gebäudes bemessen und analysiert. Die Ergebnisse wurden dann verwendet, um ein detailliertes Innenraummesssystem zu entwickelt und an verschiedenen Standorten in Berlin aufzubauen. Lufttemperatur, mittlere Strahlungstemperatur, relative Feuchte sowie Luftströmungen wurden insgesamt in 31 Räume in acht unterschiedlichen Gebäuden von Sommer 2013 bis Sommer 2015 durchgängig bemessen. Die erhobenen Daten wurden dann verwendet, um die Variabilität von Hitzestress im Innenraum zeitlich und räumlich anhand des UTCI (Universal Thermal Climate Index) zu untersuchen. Des Weiteren wurden Außendaten von Fassadenstationen genutzt, um den Einfluss des Außenraums, als wichtigster Faktor, zu untersuchen. Den Abschluss bilden umfangreiche Analysen zu den Einflüssen von Innenraum- und Außenraumtemperaturen auf die Mortalität mittels Generalisierter Additiver Modelle (GAM).

Die Ergebnisse zeigen, dass Hitzestress im Innenraum eine ernstzunehmende Gefahr darstellt. Alle Untersuchungsräume weisen hohe thermische Belastungen auf, unabhängig in welchem Gebäudetyp bzw. wo sie sich innerhalb eines Gebäudes befinden. UTCI Werte im Innenraum schwanken zwischen 6.6 K innerhalb der Stadt und um bis zu 7 K innerhalb eines Gebäudes und weisen im Vergleich zum Außenraum sehr hohe Belastungswerte während der Nacht auf.

Die höchsten Werte wurden in modernen Gebäuden mit großen Fensterflächen ermittelt. Bezüglich der unterschiedlichen Einflussfaktoren auf das Innenraumklima konnte das Außenklima als wichtigste Einflussgröße bestätigt werden. Des Weiteren zeigt sich, dass die Innenraumtemperatur im Vergleich zur Außenraumtemperatur ein ebenso guter Prädiktor für Mortalität ist. Aufgrund der zunehmenden Verstädterung sowie der Alterung der Gesellschaft ist es wahrscheinlich, dass schädliche Hitzeeffekte in der Zukunft zunehmen werden. Zusätzlich können ansteigende Temperaturen, verursacht durch den Klimawandel, die Situation noch verstärken.

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CHAPTER 1: INTRODUCTION

1.1 Urban climate and heat stress

Extreme heat events are one of the most devastating natural extreme events worldwide and have caused thousands of additional deaths in past decades (WHO 2015). The Intergovernmental Panel on Climate Change (IPCC) has projected that increases in the frequency, duration and/or intensity of heat waves are likely to occur in urban areas of Europe as a result of climate change (IPCC 2013b). Even if these events are initially infrequent and not as dangerous as, for example, storm events and earthquakes, they will increase mortality rates, economic loss and severe health issues on a global scale (Changnon et al. 2000, Schär & Jendritzky 2004, Gosling et al. 2009, Burkart et al. 2014).

There are no generally accepted definitions of heat wave or heat event and thus these terms are not used consistently. However, all definitions indicate that these events represent multiple consecutive days with extraordinarily high air temperatures (Meehl & Tebaldi 2004). Moreover, heat waves cause significant increases in mortality and morbidity rates (Kovats & Hajat 2008, Scherer et al. 2013, Guo et al. 2014). For instance, in 2003, Western Europe experienced one of its worst heat waves which resulted in an estimated 70,000 heat-related deaths after two weeks of extraordinarily high temperatures (Robine et al. 2008). France was the worst affected country, more than 14,800 recorded heat-related deaths (Dhainaut et al. 2004, Pirard et al. 2005). Heat waves are the leading cause of weather-related deaths in the United States with an estimated 688 deaths reported to be directly related to heat each year (CDC 2006). In 2010, Russia experienced an unprecedented heat wave that resulted in approximately 15,000 heat-related deaths (Dole et al. 2011), and as recently as February 2017, Australia recorded temperatures of approximately 48 °C. Sydney suffered eleven days in a row from temperatures about the 35 °C threshold (DWD 2017).

Within the last few years, studies have focused on the possible influence of rising air temperatures due to climate change on the frequency and intensity of heat waves (Meehl & Tebaldi 2004, Schär et al. 2004, Mitchell et al. 2006, Luber & McGeehin

2008, Kyselý 2010, Gershunov & Guirguis 2012). Currently, the number month of record-breaking heat month is, on average, five times higher than that in a non-warming climate (Coumou et al. 2013). In conclusion, there is an 80 % possibility that climate change is responsible for newly occurring monthly heat records due to rising temperatures. In Germany, 2016, 2015 and 2014 were among the top five hottest years since official measurements began in 1881 (DWD 2016). From 1881 until 2015, the mean annual air temperature in Germany increased by approximately 1.4 °C. Additionally, the 30-year annual mean of the reference period 1961-1990 increased from 8.2 °C to 8.9 °C within the current period of 1981-2010 (DWD 2016). Due to the trend of increasing temperatures and the high numbers of heat events during the last decade, the German Weather Service (DWD) extended and improved its warning system starting at the beginning of May 2017 and emphasizes the importance of necessary measures.

Urban areas are of specific interest within the new heat warning system of the DWD. Cities experience higher temperatures than their rural surroundings, and people living in these urban areas are hence at higher risk (McCarthy et al. 2010). This effect is known as the urban heat island effect (UHI). UHIs are affected by urban structures, topography, season, time of day and climate (Grimmond et al. 2010). The main drivers are a modified energy balance with an increased sensible heat flux because of the presence of more artificial surfaces and an increased surface area, as well as the decreased latent heat flux due to smaller vegetation cover (Oke 1982, Arnfield 2003, Kanda 2006). Furthermore, these drivers are supplemented by a greater amount of thermal inertia and heat storage caused by the higher heat capacity of buildings and other artificial surfaces, complex processes of radiation due to shading and multiple reflections, and changes in the emissivity of long-wave radiation and anthropogenic heat fluxes (Barlow 2014, Zhao et al. 2014). UHIs typically reach their highest intensities during summer night due to the high amount of heat release of artificial surfaces compared to areas with vegetation (Oke 1981). This leads to an additional higher thermal load at night compared to rural areas. In daytime, the higher aerodynamic resistance in cities is additionally responsible for higher temperatures due to lower convection rates compared with rural areas (Zhao et al. 2014). Temperature differences can hence be up to several Kelvin between cities and their rural surroundings (Oke 1982). The intensity of the UHI effect varies between cities and depends on several factors such as urban morphology, physical characteristics, waste heat release, regional climate factors and the urban extent (Arnfield 2003, Kanda 2006, Santamouris 2015). In addition to higher temperatures in urban areas, the increasing population of cities is an important consideration. By 2050, urbanization will result in 6 billion urban dwellers globally (McCarthy et al. 2010). In Germany, 70 % of the population is already living in urban areas, and this proportion is expected to increase to greater than 80% by 2050, with a corresponding decrease in the rural population (UN 2014). Consequently, population density and urban growth will accelerate accompanied by an increase in artificial materials and sealed areas, which will further intensify the UHI and hence the thermal strain. The steadily increasing urban population will lead to higher numbers of people threatened by heat stress (IPCC 2013b, Scherer et al. 2013).

Heat stress is a serious risk to humans and occurs when the natural balance of the human body between heat production and heat release is disturbed. To maintain a core temperature of 37 °C, the regulatory system can adjust to surrounding temperatures through conduction, convection, radiation and evaporation (Kovats & Hajat 2008). However, increases in air temperature have the potential to compromise the human body's ability to maintain thermoregulation. Consequently, the core temperature increases, which can cause adverse health effects such as reduced mental and physical abilities and increased morbidity and mortality (Gosling et al. 2014). For example, a significant increase in mortality due to heat stress has been shown by Michelozzi et al. (2009a), D'Ippoliti et al. (2010), Gabriel and Endlicher (2011), Ye et al. (2012), Almeida et al. (2013). Analyses of heat stress and morbidity (McGeehin & Mirabelli 2001, Monteiro et al. 2013, Scherber 2014), and impacts on human well-being (Kjellstrom & McMichael 2013), have shown significant results as well.

The term biometeorology summarizes the interdisciplinary science that considers the interactions between atmospheric processes and humans (Gosling et al. 2014). To estimate human-biometeorological conditions, more than 100 different indices have been developed combining different climate elements, such as short- and long-wave radiation, air temperature, atmospheric moisture and wind speed, into a single value (Blazejczyk et al. 2012). According to Parson (2003) thermal stress indices can be divided into three groups: 1) *direct indices*, which are based on direct measurements, e.g., the apparent temperature (Steadman 1979); 2) *empirical indices*, which are based on objective and subjective strains, e.g., the physiological strain index (Moran et al. 1998); and 3) *rational indices*, which are based on calculations involving the heat balance equation, e.g., the universal thermal climate index (UTCI) (Jendritzky et al. 2012). Even rational indices require additional input variables, they highlight the stages involved in understanding the relationship between thermal environments and human thermal perception (Blazejczyk et al. 2012). The latest thermal index is the recently developed UTCI (Jendritzky et al. 2012). The UTCI is based on a multi-node model of human heat transfer and temperature regulation (Fiala et al. 2012). Furthermore, an up-to-date clothing model takes into account typical dressing behaviors in different thermal conditions and is further representative of European and North American urban populations in outdoor spaces (Havenith et al. 2012). Following the principles of equivalent temperature, it provides a continuous scale (°C) and an ordinal scale representing thermal stress categories (Jendritzky et al. 2012, Bröde et al. 2013). Regarding meteorological input variables, the UTCI is calculated based on the mean radiant temperature, air temperature, wind speed and atmospheric humidity. Bröde et al. (2012) has provided a detailed description of the operational procedure for calculating the UTCI.

1.2 Indoor climate

In addition to the steady increase in studies of heat stress and its implications for human health, recent studies have begun focusing on indoor environments. Outdoor environments have been the major objectives of previous studies, and indoor climate was often neglected; occasionally, meteorological variables were even set equal to the outdoor climate (Kántor & Unger 2011). However, in industrialized countries, people spend an average of 90 % of their day in confined environments, with a value close to 100 % for the sick and elderly, and are hence mostly exposed to the indoor climate (Höppe 1993, Brasche & Bischof 2005). Heat stress in outdoor environments is well investigated, and several adaptation and mitigation measures have been established and tested (Kim et al. 2014, Schuster et al. 2017). The most mentioned are changes in the actual habitation (e.g., sunny to shade) and reductions of physical activity and exposure times (Höppe 2002). Adaptation measures in indoor environments are limited compared to outdoors. It is rarely possible to change location, and activity is mostly limited to sedentary positions. In particular, during night and at work, the exposure time to the indoor climate comprises several hours during which none of the mentioned measures can be applied. Therefore, it has been postulated that night temperatures may impact health negatively due to the absence of overnight relief from heat experienced during the day (WHO 2004).

The driving factors of indoor climate are manifold. First, indoor climate is driven by outdoor climate (Smargiassi et al. 2008, White-Newsome et al. 2012, Nguyen et al. 2014). As outdoor temperature varies on a spatial and temporal scale within a city, indoor temperature will likely differ within the urban area as well (Fenner et al. 2014). Outdoor climate affects indoor climate mainly by exchange through the building envelopes. However, the relationship is not completely linear and depends on several other factors, such as building characteristics, user behavior or active and passive cooling systems. The diurnal course of outdoor air temperature is dampened in indoor environments as an effect of heat transfer by the walls (Höppe 1993). This heat transfer resistance of the walls depends on the materials used. Frieß (2002) showed, for example, that walls composed of concrete have higher resistance than windows and consequently a lower increase in temperature. Buildings with a high percentage of glass surfaces are hence at higher risk due to the high heat conduction. Modern architecture has undergone an increasing trend of using mainly glass facades. With increasing summer temperatures, this increased use of glass can only be counteracted through the use of active or passive cooling systems. Air conditioning is not currently common in Germany as an adaptive prevention for elevated indoor temperatures, but its use is likely to increase. In terms of sustainability and the use of air conditioning, research has shown that for every one degree increase in outdoor temperatures, the demand for cooling energy jumps by 5% to 20% (Anderson et al. 2013). Thus, in terms of energy conservation and reducing carbon emissions, alternative forms of cooling systems or architecture to maintain indoor temperature must be sought. The position within a building also tends to influence the exposure rate to heat. Higher floors of a building and especially floors close to the roof show higher temperatures during day and night (Koppe et al. 2004).

Another driving factor to consider is the behavior of the people within the buildings or rooms. Adaptation measures, such as closing windows during the day and opening them during night or shading the room through the use of, for example, blinds to control radiation, are useless or even counterproductive if people do not know to use them or use them incorrectly. Only a few studies have considered user behavior. However, a study by Pfafferott and Becker (2008) distinguished between passive or active user behavior and showed that reasonable user behavior can reduce the maximum indoor air temperature by 4 Kelvin. The need to consider user behavior becomes apparent when analyzing indoor heat exposure in vulnerable populations. Elderly people are at particular higher risk because they are often not able to use measures to reduce heat stress due to their limited mobility and self-supply (Koppe et al. 2004, Huang et al. 2013). In addition to their intensive care needs, changes in the thermoregulatory system due to aging (Flynn et al. 2005, Grundy 2006) or pre-existing illnesses and continuous medication use increase their vulnerability. Elderly subjects have a lower threshold for the development of renal failure and diminished renal tubular conservation of sodium and water during periods of dehydration. A further contributor to risk in hot weather occurs when older subjects are unable to obtain sufficient volumes of water for themselves due to infirmity or impaired thirst during such periods of excessive loss of fluid (Flynn et al. 2005). These circumstances result in continuous high numbers of deaths among the elderly during heat waves, regardless of whether they are at home, in hospital or in residential facilities (Fouillet et al. 2006, Kovats & Hajat 2008).

Demographic change is, of course, not an indoor issue but remains an essential consideration with respect to the threat of heat stress to vulnerable groups. Population aging is expected to increase the proportion of vulnerable people (Wilhelmi & Hayden 2010, Huang et al. 2013, Fernandez Milan & Creutzig 2015). The percentage of older people (> 65 years) living in Germany will increase from 21 % currently to 29 % (bpb 2016) and in Berlin, the largest city in Germany, from 19 % currently to 22 % by the year 2030 (SenStadtUm 2016). In 2030, 844,000 inhabitants of Berlin will older than 65 years of age. An even greater increase will occur in the proportion of those older than 80 years, from 162,000 to 263,000, an increase of approximately 62 % (from 4.6 % to 7.0 % of the population).

A direct determination of indoor climate on the basis of outdoor climate is hence difficult due to the presence of many other influencing factors, such as the characteristics of the building, human-induced cooling systems and user behavior.

1.3 Research objectives

This thesis is dedicated to the investigation of indoor heat stress during day and night in buildings using Berlin as an exemplary city. Therefore, I have developed and established a detailed indoor measurement system distributed over the city to measure indoor climate and heat stress in particular over a continuous period of at least three years. The main criteria for the study sites were as follows: 1) buildings in different districts with different UHI intensities; 2) different building characteristics with a wide range of year of construction and hence materials as well as different multi-story buildings; 3) different user behaviors in the buildings. The study sites were chosen to cover the main driving factors of indoor climate and based on the availability of regular access. The variety of buildings and locations within the city should overcome the limitations of previous studies regarding indoor climate measurements.

Chapters 2-4 are the core of the thesis (Figure 1). First, a measurement evaluation provided the basis for establishing a detailed measurement system for subsequent studies regarding instrumental set-up, measurement devices, and meteorological variables. Second, the measured data were processed and analyzed to assess indoor heat stress variability on a spatial and temporal scale. Finally, an application of the analysis of indoor heat exposure is provided.

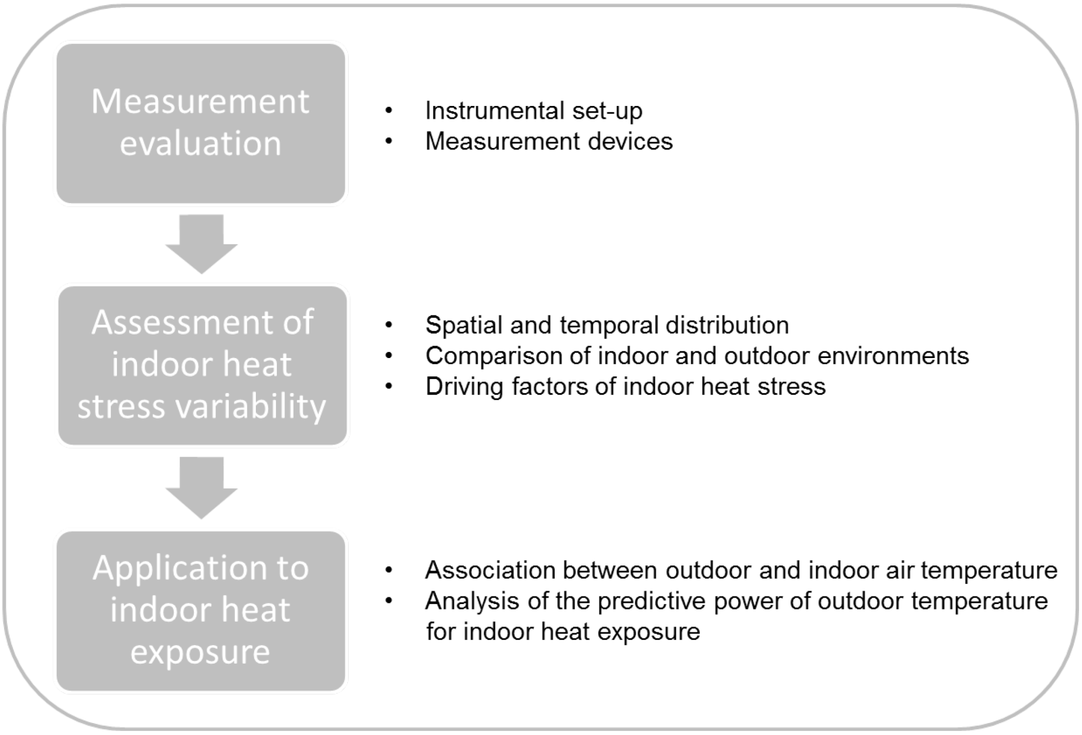

Figure 1 Overview of the structure of the thesis.

To assess heat stress in terms of human biometeorology, measurements of the meteorological variables air temperature (Ta), mean radiant temperature (Tmrt), air velocity (va) and relative humidity (rH) are necessary. Research based on the literature identified different approaches for measurement set-ups and instruments, especially for Tmrt. Chapter 2 focuses on Tmrt as the most complex variable regarding the input parameters for heat balance models for humans, which are the background for the assessment of thermally unfavorable conditions and heat stress. The first objective of this chapter is to identify the most appropriate measurement for Tmrt indoors and to confirm that there are no differences between Ta and Tmrt, as is widely assumed in the scientific literature (Matzarakis & Amelung 2008, Kántor & Unger 2011, Langner et al. 2013). Five different methods of obtaining Tmrt in indoor environments are compared. Furthermore, differences between Ta and Tmrt within a single room, especially at higher air temperatures, are analyzed and subsequently discussed. The third part of this chapter investigates the possible reasons for the differences between Ta and Tmrt. This part relies on the assumption that the surrounding walls are not uniform and that differences in surface temperatures may influence Tmrt. Additionally, it is assumed that direct solar radiation influences Tmrt. Different building stock characteristics (wall exposition, floor levels and room and window size) may play a role in determining indoor climate and are also considered. The results of this study constitute the basis for the indoor measurement system in terms of measurement devices and instrumental set-up.

Chapter 3 presents the results of the first two years of indoor measurements within eight different buildings and 31 rooms. The chief objective of this chapter is to examine the spatial and temporal variability of indoor heat stress in different buildings in Berlin. Therefore, the UTCI is calculated to consider the main meteorological parameters Ta, RH, Tmrt, and va. Previous studies focusing on indoor thermal conditions in urban areas have only used Ta as the describing or forcing variable (Mirzaei et al. 2012, White-Newsome et al. 2012, Beizaee et al. 2013). Furthermore, heat warning periods are examined to estimate the maximal thermal load during day and night and to determine if the warning periods require revision. In a second step, the main driving factors of indoor climate regarding outdoor climate and building characteristics are analyzed. For outdoor conditions, the UTCI is calculated based on on-site data to consider local climate variations in urban areas. Previous studies used only central weather stations to assess the outdoor conditions (Nguyen et al. 2014, Quinn et al. 2014) and neglected potential spatial and temporal differences (Fenner et al. 2014). To evaluate the results, data from a central weather station are also used. The building characteristics of floor level, window size, and year of construction are considered to estimate differences between and within the observed buildings.

Because indoor climate is not measured regularly or even continuously, in contrast to outdoor climate, and is mainly driven by outdoor climate, Chapter 4 assesses the adequacy of outdoor air temperature as a measure for assessing indoor heat exposure during the day and night. This study follows Chapter 2 and 3, which indicate that indoor heat stress is a severe threat and must be considered in human health. Outdoor data are usually easily accessible, intensely measured and standardized. Outdoor data are used from central weather stations distributed over Berlin and indoor data acquired from the measurement system developed as part of this thesis. Chapter 4 can be divided into three steps: Initially, (1) the association between outdoor air temperature and indoor air temperature over the 2-year measurement period from 05/01/2013 until 04/30/2015 and the derived parametric relationships are analyzed. A distributed lag non-linear model (dlnm) is further used to identify time displacements between outdoor and indoor temperatures. Subsequently (2), this association is used to calculate indoor air temperature based on outdoor data for an extended period of ten years from 2000 to 2010. Finally, (3) generalized additive models (GAM) are fit with adjustment for various confounders to assess the predictive power of outdoor vs indoor temperatures for indoor heat exposure and hence mortality.

Chapter 5 constitutes the synthesis of the thesis through a summary and discussion of the main findings. A subsequent chapter focuses on the limitations of the work followed by potentially relevant future research possibilities. The thesis closes with the overall conclusion of the work.

1.4 Structure of the thesis

The dissertation is presented in cumulative form and consists of three individual manuscripts, which are reproduced in Chapter 2-4. Two manuscripts are published whereas the third one is submitted and under review, thus fulfilling the formal requirement of a cumulative doctoral dissertation. Chapter 5 summarises the outcome of the three chapters and synthesizes their findings. The nature of a cumulative dissertation envisaging publication in a variety of international publications means that a certain amount of repetition in the thesis could not be avoided. Additionally, minor inconsistencies concerning formal criteria (e.g., British vs. American English) were inevitable. The three chapters are as follows:

Chapter 2: Walikewitz N., Jänicke B., Langner M., Meier F., Endlicher W. (2015): The difference between the mean radiant temperature and the air temperature within indoor environments: A case study during summer conditions. Building and Environment 84: 151-161.

Chapter 3: Walikewitz N., Jänicke B., Langner M., Endlicher, W. (2015): Assessment of indoor heat stress variability in summer and during heat warnings: A case study using the UTCI in Berlin, Germany. International Journal of Biometeorology, Students and New Professionals: 1-14.

Chapter 4: Walikewitz N., Burkart K., Endlicher W. (2017): Analysis of outdoor air temperature as an adequate measure to assess indoor heat exposure. Indoor air (submitted)

One appendix supplements the thesis:

Appendix 1: Supplementary material provided with the manuscript "Walikewitz N., Burkart K., Endlicher W. (2017): Analysis of outdoor air temperature as an adequate measure to assess indoor heat exposure. The Science of the Total Environment (submitted)"

1.5 The author's contribution to the individual publications

The publications in this thesis are based on data obtained from a detailed indoor measurement network distributed over Berlin. I established the measurement network by looking for appropriate locations and installed the measurement devices. Marcel Langner supported me by the selection of the devices. Further, I collected data over the whole measurement period of three years.

Chapter 2: I developed the research design in close cooperation with Marcel Langner. I conducted the literature recherche, established the measurement concept, collected, analysed and interpreted the data. Furthermore, I wrote the entire manuscript. Britta Jänicke assisted with measurement instruments and research design. Marcel Langner, Fred Meier, Britta Jänicke and Wilfried Endlicher critically reviewed the manuscript and discussed the findings and interpretation.

Chapter 3: I designed the research concept in cooperation with Britta Jänicke. I reviewed the relevant literature and collected, analysed and interpreted the data. Moreover, I wrote the entire manuscript. Marcel Langner, Britta Jänicke and Wilfried Endlicher critically reviewed the manuscript and discussed the findings and interpretation.

Chapter 4: I developed the research design in close cooperation with Katrin Burkart. I collected, analysed and interpreted the data and wrote the entire manuscript. Katrin Burkart contributed to the statistical analysis and critically reviewed the manuscript and discussed the results and interpretation. Wilfried Endlicher reviewed the manuscript and advised me through the whole work.

CHAPTER 2: THE DIFFERENCE BETWEEN THE MEAN RADIANT TEMPERATURE AND THE AIR TEMPERATURE WITHIN INDOOR ENVIRONMENTS: A CASE STUDY DURING SUMMER CONDITIONS

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Published in:
Building and Environment 84 (2014): 151-161

Abstract

The mean radiant temperature (Tmrt) is the most complex variable regarding the input parameters for heat balance models of human being that are the background for the assessment of thermally unfavourable conditions and heat stress. This paper investigates the simplification of past studies that the Tmrt is equal to the air temperature (Ta) under indoor conditions. In a second step, the causes for deviations between the two parameters are examined and integrated into the context of indoor climate. Measurements were conducted in four rooms at the Geography Department of Humboldt University in Berlin during autochthonal weather conditions from the 16th of August to the 2nd of September 2013. Tmrt was derived using integral radiation measurements and three different types of globe thermometers.

The study indicates that the deviations between the different methods of obtaining Tmrt are negligible for indoor environments. The results show that the differences between Ta and Tmrt are negligible during most periods, as stated in previous literature. As air temperatures increase, however, Tmrt exceeds Ta up to 1.3 K. The examination of the surface temperatures indicates that rooms with window walls facing southeast and southwest show the largest disparities between Ta and Tmrt. The correlation between Ta and Tmrt and the sum of the short and long wave radiation specifies the radiation intensity and duration as the main driver of Tmrt. Future studies on indoor heat stress should hence consider that Tmrt and Ta can differ depending on the characteristics of the room and on solar radiation.

Keywords: indoor climate, mean radiant temperature, integral radiation measurements, globe thermometer

2.1 Introduction

Heat stress is a serious environmental risk to humans. In cities where the urban heat island effect causes additional higher air temperatures (Oke 1982), the probability of adverse thermal conditions is above average. Additionally, the global increase in air temperature due to climate change is likely to intensify the risk to humans in urban agglomerations (Matzarakis & Endler 2010) and it is further suggested that climate change may amplify the UHI effect in some locations (McCarthy et al. 2010).

Citizens in industrialised countries spend approximately 90% of their day in confined spaces and are mostly exposed to the indoor climate (Höppe 1993). Building materials and different systems of heating and cooling now influence indoor climates. In many mid-latitude countries, such as Germany, however, air-conditioning of buildings is not common. In areas where the probability of more frequent and intense hot days and nights increases (IPCC 2013b), unfavourable thermal conditions can become a major heat stress problem. There are many risks related to heat stress in outdoor and indoor spaces. An increase in mortality rates has been identified and quantified by McMichael and Haines (1997), Smoyer et al. (2000), Michelozzi et al. (2009a), D'Ippoliti et al. (2010), Gabriel and Endlicher (2011), Ye et al. (2012), Almeida et al. (2013), Scherer et al. (2013). The impact of heat stress on morbidity is also evident, as shown by Scherber et al. (2013), Monteiro et al. (2013) and McGeehin and Mirabelli (2001). These studies reveal the relation between heat stress related risks and hazardous atmospheric conditions outdoors. However, only a limited number of studies examine the role of indoor climates for hazardous atmospheric conditions (Pfafferott & Becker 2008). In addition to the impact on human health, heat stress also influences human well-being (Kjellstrom & McMichael 2013). Negative effects on the performance of office work have also been determined (Witterseh et al. 2004, Lundgren et al. 2013). Several studies over the last few years have considered the effects of warmer indoor temperatures in urban areas (Mirzaei et al. 2012, Beizaee et al. 2013).

The most important meteorological variables regarding thermal conditions and heat stress are air temperature (Ta), relative humidity (RH), wind velocity (va) and the mean radiant temperature (Tmrt). The determination of Tmrt is a classic problem in the field of human bioclimatology. Tmrt is defined as the uniform temperature of a hypothetical spherical surface surrounding the subject (emissivity ε=1) that would result in the same net radiation energy exchange with the subject as the actual, complex radiative environment (Matzarakis et al. 2007). The importance of Tmrt is apparent when assessing the human bioclimate within heat stress analyses. Tmrt is required to calculate thermal indices such as the UTCI (Universal Thermal Climate Index) (Jendritzky et al. 2012), the PT (Perceived Temperature) (Staiger et al. 2012), the PMV (Predicted Mean Vote) (Fanger 1973) and the PET (Physiologically Equivalent Temperature) (Höppe 1999, Matzarakis et al. 1999). Research has shown several ways of calculating or measuring Tmrt (Kántor & Unger 2011, d'Ambrosio Alfano et al. 2013, Johansson et al. in press). Complex radiation measurements from all six directions were conducted by Spagnolo and de Dear (2003), Thorsson et al. (2006), Matzarakis et al. (2007), Thorsson et al. (2007). A globe thermometer in combination with wind speed and air temperature observations, a more frequently used method, was used by Bedford and Warner (1934), Kuehn et al. (1970), Glück (2006), Thorsson et al. (2007). Langner et al. (2013) assessed indoor heat stress in different buildings in Berlin using the UTCI. The study identified differences in the mean air temperature (4.9 K) and mean UTCI (4.4 K) within the building of the Geography Department of Humboldt University. In contrast to outdoor conditions, where Tmrt can be more than 30K above Ta (Mayer et al. 2008) and shows a clear spatial pattern (Lindberg et al. 2014), the differences indoors may be assumed to be small, based on the hypothesis that surrounding indoor surfaces have uniform temperatures and radiation fluxes (VDI 2008). As a consequence, indoor climate studies have been often limited to the assumption that the mean radiant temperature is equal to air temperature (Matzarakis & Amelung 2008, Kántor & Unger 2011, Langner et al. 2013). Possible differences between Ta and Tmrt might influence the evaluation of thermal comfort. Especially the underestimation of Tmrt could affect the assessment of indoor heat stress through for example variations of thermal indices. The study of d'Ambrosio Alfano et al. (2013) reviews the typical measurement methodologies of Tmrt indoors, combined with a comparative analysis of the meteorological performances and practical principles. Their results indicate a high sensitivity of the thermal index PMV to the choice of sensors and methods.

So far, there is no experimental study that quantifies the differences between Tmrt and Ta indoor. Therefore, this study was designed to evaluate whether Tmrt is equal to Ta in due consideration of indoor characteristics. The first aim of the study is to compare five different methods of obtaining the Tmrt in indoor environments. The second aim is to investigate, whether there are differences between Ta and Tmrt (equation 1) in a single room, especially at higher air temperatures, or if both measures are equally suitable. The third aim of the study is to investigate the possible reasons for ΔT_{a-mrt}. This part relies on the assumption that the surrounding walls are not uniform, and differences in surface temperatures may influence Tmrt. Additionally, it is assumed that direct solar radiation influences Tmrt. Different building stock characteristics (wall exposition, floor levels, room and window size) may play a role in determining indoor climate and are also considered (Mavrogianni et al. 2012).

$$\Delta T_{a-mrt} = T_a - T_{mrt} \qquad (1)$$

2.2 Methods

2.2.1 Study design

The measurements were conducted in four different rooms (R1-4) at the Geography Department of Humboldt University in Berlin (52°25'N 13°32'E), which was constructed in 2003 (Fig 2.1; Tab 2.1). From the 16th of August 2013 to the 2nd of September 2013 each room was equipped with a set of meteorological instruments (see 2.2). Placing sensors at locations where they may be influenced by direct sunlight was avoided to estimate the general indoor conditions and because of known deficits regarding the assessment of the detailed integral radiation measurements (Park & Tuller 2011, Kántor et al. 2013) as well as for the remaining sensors. Because of instrument limitations, integral radiation measurements were collected over a time span of four days per room. Additionally, surface temperatures (Ts) based on measurements with a contact thermometer (Tsc) and based on thermal infrared images (Tst) of the inner walls were collected over a 24 h period on the 19^{th} (R2), 22^{nd} (R3), 26^{th} (R4) and 29^{th} (R1) of

August once per hour in each room. All data were aggregated to mean hourly values, and the analysis was conducted using the software program R Version 2.15.1 (RCoreTeam 2012). To examine the unaffected characteristics of the rooms, no air ventilation or other measures that might have interfered with the room climate were employed. The four 24 h analyses were conducted under autochthonal weather conditions, except in R2 (19^{th} of August), where the cloud cover increased during the day. All measurements were registered in Central European Time (CET).

Table 2.1 Characteristics of the study rooms (R1-4); SW=southwest; SE=southeast; NW=northwest, NE=northeast

	Ground floor (R1)	**First floor (R2)**	**Second floor (R3)**	**Second floor (R4)**
Volume (m^3)	223	192	227	122
Window size (m^2)	26	20	31	21
Exposition (window)	SW; (SE partly opaque glass)	SW	SE	NW
Outer walls	SW; SE	SW; SE	NE; SE	SW; NW

Table 2.2 Overview of the five different methods of deriving the mean radiant temperature

Abbreviation	**Method**
TmrtGB	black globe thermometer; 150 mm diameter; 0.4 mm thickness
TmrtGG1	grey globe thermometer (RAL 7001); 40 mm diameter; 1 mm thickness
TmrtGG2	grey globe thermometer (RAL 7011); 40 mm diameter; 1 mm thickness
TmrtI	Integral radiation measurement for a sitting person
TmrtIS	Integral radiation measurement for a standing person

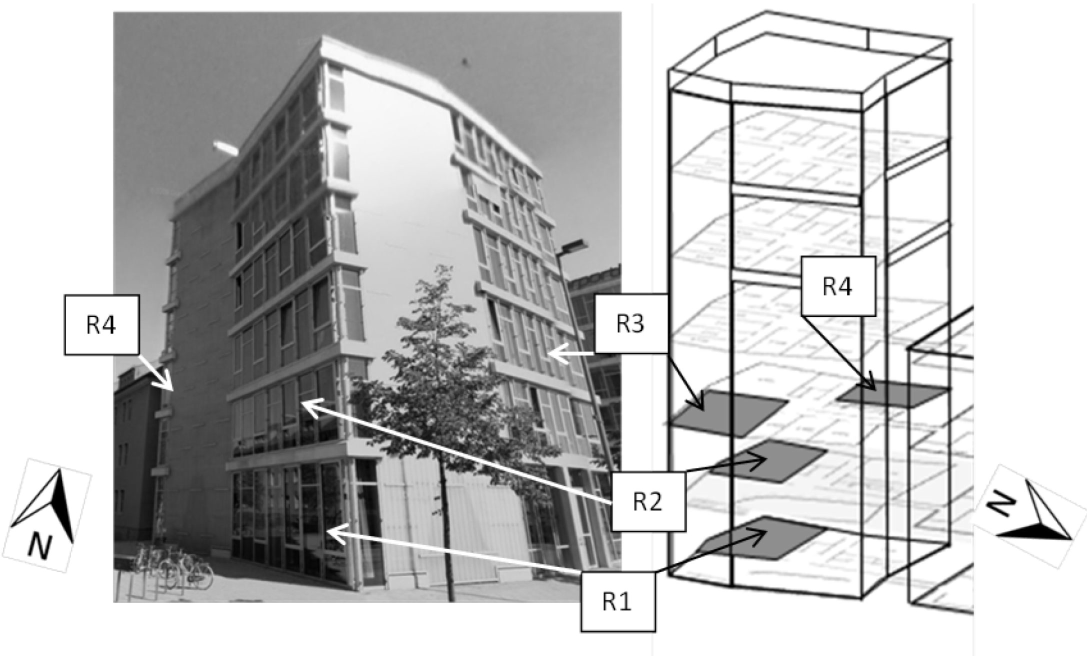


Figure 2.1 Studied rooms (R1-4) at the Geography Department at Humboldt University; the shaded areas indicate the rooms where the indoor measurements were collected

2.2.2 Instrumental setup

The analysis was conducted using five different ways of measuring and calculating Tmrt in four rooms (Tab 2.2). This step was followed by a comparison of Tmrt with Ta, through the calculation of differences over daily-cycles ($\Delta T_{a-mrtGB}$, $\Delta T_{a-mrtGG}$and $\Delta T_{a-mrtIS}$). To study the sources of the disparities, surface temperatures (Tsc and Tst) as well short (SW) and long wave (LW) radiation and the sum of short and long wave radiation (RAD) were examined. In contrast to equation (3), RAD was summed without weighting factors because the calculation considers just one wall, either the window or the opposite wall per room.

Tsc values were measured at three or up to six points per wall with a contact thermometer (Testo 925; ±0.5 °C) at a height of 1.1 m once per hour over a period of 24 hours. The number of measurement points depended on the size of the wall and on how many different materials were found. The Tst values of every surrounding wall were collected every hour using a thermal infrared camera (FLIR B365). For the analysis, a smaller region of interest (ROI=4.5 m^2) of every wall was collected to exclude influences from the subsequent walls or of furniture in front of the wall. Each room was equipped with three Testo 174H loggers to measure the air temperature and relative humidity (accuracy of ±0.5 °C and ±3 %RH, respectively). The sensors were fixed at a height of approximately 1.1 m above the ground, corresponding to the average height of the centre of gravity for adults (Mayer & Höppe 1987). The sampling rate was set to 5 minutes.

Tmrt can be measured using a globe thermometer (Bedford & Warner 1934, Kuehn et al. 1970). Each room was prepared with two black globe thermometers (±0.5 °C) and the sampling rate was set to 5 minutes. These black-painted hollow copper spheres (150 mm in diameter; 0.4 mm thickness) have a Pt100 sensor at their centres, where the temperature is measured (Tg). The black globes were placed at a height of 2 m due to the additional use of the instruments within another long term study in the frequently used seminar rooms. Comparative measurements at 1.1 m were done over a 24h period to ensure that no influence due to different installing heights occurs. The results of the measurements are presented as TmrtGB. Another globe thermometer, introduced by Humphreys (1977) and evaluated by Thorsson et al. (2007), was used. This hollow acrylic sphere covered with flat grey paint (RAL 7001) has a diameter of 40 mm and a thickness of 1 mm and has less inertia under changing conditions. Additionally, as suggested by Thorsson et al. (2007), another globe thermometer of the same size but with a slightly darker colour (RAL 7011) and hence, a lower albedo was used. The temperature was recorded with a Type-T thermocouple at the centre of the globe, and the sampling rate was set to one minute. The results of these measurements are presented as TmrtGG1 (RAL 7001) and TmrtGG2 (RAL 7011), respectively. To calculate TmrtGG1 and TmrtGG2, va and Ta were recorded using a WindMaster 1590-PK-020 (Gill Instruments Limited; < 1.5 % RMS) and a CS 215 temperature sensor (Campbell Scientific inc.; ±0.3 °C) (Fig 2.2). Tmrt was also determined through the performance of a detailed integral radiation measurement. All three-dimensional short- and long-wave radiation flux densities (Kipp & Zonen, CNR4 Net Radiometer; uncertainty in daily totals <5%) were measured with a micrometeorological station every minute at a height of 1.1 m above the ground (Fig 2.2). The instrument was positioned perpendicular to the surrounding walls, and three net radiometers independently measured the four radiation components. Timing offsets were detected because the observations were collected by different logger systems. The offsets were determined by cross correlations (5 to 210 minutes, depending on the measurement period) and removed with high certainty (correlation coefficient R≥0.95). The results of the integrated measurements are presented as TmrtI for a standing person and TmrtIS for a seated person, with all cardinal points weighted equally. Due to the fact that the detailed integral radiation measurement is the most accurate technique (Spagnolo & de Dear 2003, Thorsson et al. 2007), TmrtIS was used as a reference.

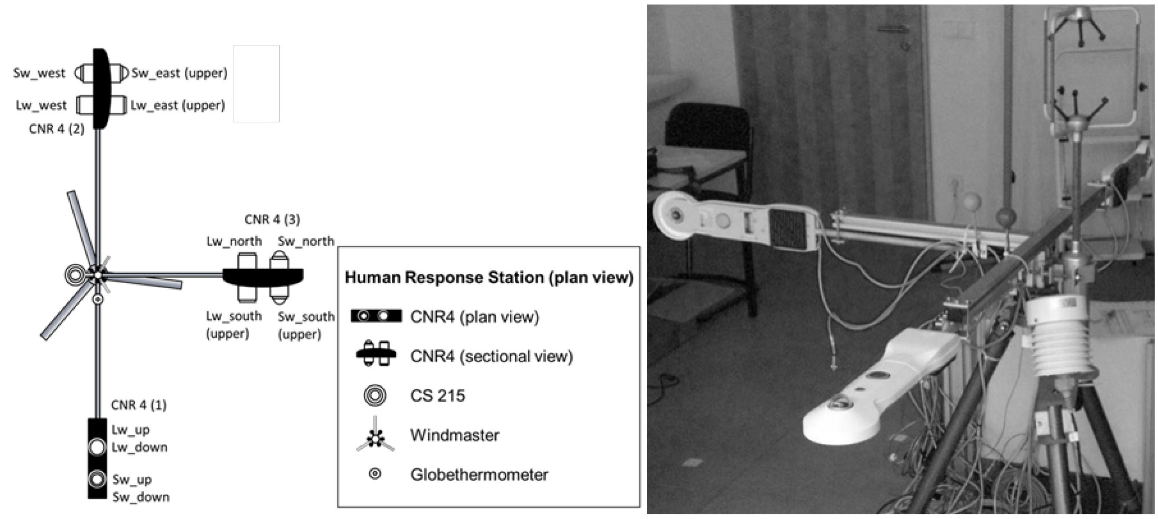


Figure 2.2 Instrument setup for the indoor measurements; left: plan view of the micrometeorological station with the three-dimensional short- and long-wave radiation sensors (CNR), sonic anemometer (WindMaster 1590-PK-020) and humidity and air temperature probes (CS 215); right: picture of the used micrometeorological station

2.2.3 Calculation of the mean radiant temperature

Kuehn et al. (1970) explained the theory of the globe thermometer in detail. This instrument has been used in several analyses and reviews to determine Tmrt (Johansson et al. in press). The temperature at equilibrium in the thermometer results from a balance between the heat gained and lost by radiation and through convection. The temperature exhibits the weighted average of radiant and ambient temperatures.

Equation (2) calculates Tmrt, provided that Tg, Ta and va are known (Thorsson et al. 2007, VDI 2008).

$$Tmrt = \sqrt{(Tg + 273.15)^4 + \frac{h_{cg}}{\varepsilon * D^{0.4}} * (Tg - Ta)} - 273.15 \qquad (2)$$

h_{cg} the globe´s mean convection coefficient

$$Black\ globe = 1.1 * 10^8 * va^{0.6}$$

$$Gray\ globe = 1.335 * 10^8 * va^{0.71}$$

va wind velocity [m/s]

ε emissivity of sphere (=0.95)

D diameter of the sphere [mm]

Tg globe temperature [°C]

Ta air temperature [°C]

The equations and results from Thorsson et al. (2007) were used to calculate Tmrt using integral radiation measurements. The mean radiant flux density (S_{str}) can be calculated by multiplying the angular factors $F_i(i = 1 - 6)$ between a person and the surrounding surfaces with six individual measurements of the short-wave radiation and long-wave radiation fluxes (VDI 2008).

$$S_{str} = \alpha_k \sum_{i=1}^{6} K_i F_i + \varepsilon_p \sum_{i=1}^{6} L_i F_i \qquad (3)$$

K_i short-wave radiation fluxes ($i = 1 - 6$)

L_i long-wave radiation fluxes ($i = 1 - 6$)

F_i angular factors between a person and the surrounding surfaces

α_k absorption coefficient for short-wave radiation (standard value 0.7)

ε_p emissivity of the human body (standard value 0.97)

According to Thorsson et al. (2007), F_i depends on the position and orientation of the person (VDI 2008). It was set to 0.22 for radiation fluxes from the four cardinal points and to 0.06 for the radiation fluxes from above and below for a standing person. For a sphere (representing a sitting person), F_i is 0.167 for all six directions. Equation (4) calculates Tmrt according to the Stefan-Boltzmann law.

$$T_{mrt} = \sqrt[4]{\left(S_{str}/(\mathcal{E}_p\sigma)\right)} - 273.15 \qquad (4)$$

σ Stefan-Boltzmann constant ($5.67 * 10^{-8}$ $Wm^{-2}K^{-4}$)

2.3 Results

2.3.1 Temporal course of the Tmrt

Table 2.3 summarises Ta and all measured Tmrt values in each room. TmrtGG1 and TmrtGG2 show the same results and are combined in the following analysis to create TmrtGG. The only small differences between TmrtI and TmrtIS can be ascribed to higher weighting factor F_i for the horizontal receivers. Due to the small differences and because the weighting factors of TmrtIS are equivalent to that of a sphere as represented by the globe instruments, TmrtIS will be used as a reference.

In the mean course of the day, the three Tmrt (TmrtGB, TmrtGG, TmrtIS) values in R1 are quite similar (Fig 2.3). TmrtGB increases, on average, an hour later compared to TmrtGG and TmrtIS. During the night and early hours of the day, when temperatures are decreasing, TmrtGG falls below the others. The differences between Tmrt vary more in R2 compared to R1 (Fig 2.3). TmrtGB is lower than TmrtGG and TmrtIS throughout the whole period. The latter values are similar during increasing and high temperatures, but TmrtGG falls below TmrtIS during decreasing and low temperatures. During the first day in R3 (Fig 2.3), with, on average, lower temperatures compared to the second and third day, Tmrt differ at the maximum daily temperature and during decreasing temperatures (TmrtIS above TmrtGG and TmrtGB with the lowest values). With increasing temperatures on the second and third day, all Tmrt show the same values as well as at the daily maximum. When temperatures decrease during the night, Tmrt varies. In R4, Tmrt differ mainly during decreasing and low temperatures (Fig 2.3). The course is equal compared to the other rooms. TmrGB has the lowest and TmrtIS has the highest values.

Table 2.3 Mean values, standard deviations (sd), minimum and maximum of Ta, TmrtI, TmrtIS, TmrtGG1, TmrtGG2 and TmrtGB for the particular four day measurement periods are shown in °C; mean values and standard deviations were calculated from the mean hourly values

	Ta		**TmrtI**		**TmrtIS**		**TmrtGG1**		**TmrtGG2**		**TmrtGB**	
	mean	**sd**	**mean**	**sd**	**mean**	**sd**	**mean**	**sd**	**mean**	**sd**	**mean**	**sd**
R1	25.6	±0.7	25.8	±1.0	26.0	±1.0	25.8	±1.1	25.8	±1.1	25.8	±0.9
R2	26.2	±0.4	26.2	±0.5	26.4	±0.5	26.3	±0.6	26.3	±0.6	26.1	±0.6
R3	26.9	±0.8	27.2	±1.1	27.3	±1.0	27.1	±1.1	27.1	±1.1	26.6	±1.2
R4	26.3	±0.8	26.1	±0.8	26.3	±0.8	26.1	±0.9	26.1	±0.9	25.9	±0.8
	min	**max**	**min**	**max**	**min**	**max**	**min**	**max**	**min**	**max**	**min**	**max**
R1	24.3	27.1	24.2	28.0	24.4	28.1	24.1	28.2	24.1	28.2	24.5	28.1
R2	25.5	26.5	25.4	27.4	25.6	27.5	25.3	27.7	25.3	27.6	25.2	27.6
R3	25.4	28.7	25.5	29.9	25.7	29.9	25.4	29.8	25.4	29.8	25.1	29.8
R4	25.1	29.0	25.0	29.0	25.2	29.2	24.9	28.9	24.9	28.9	24.8	28.4

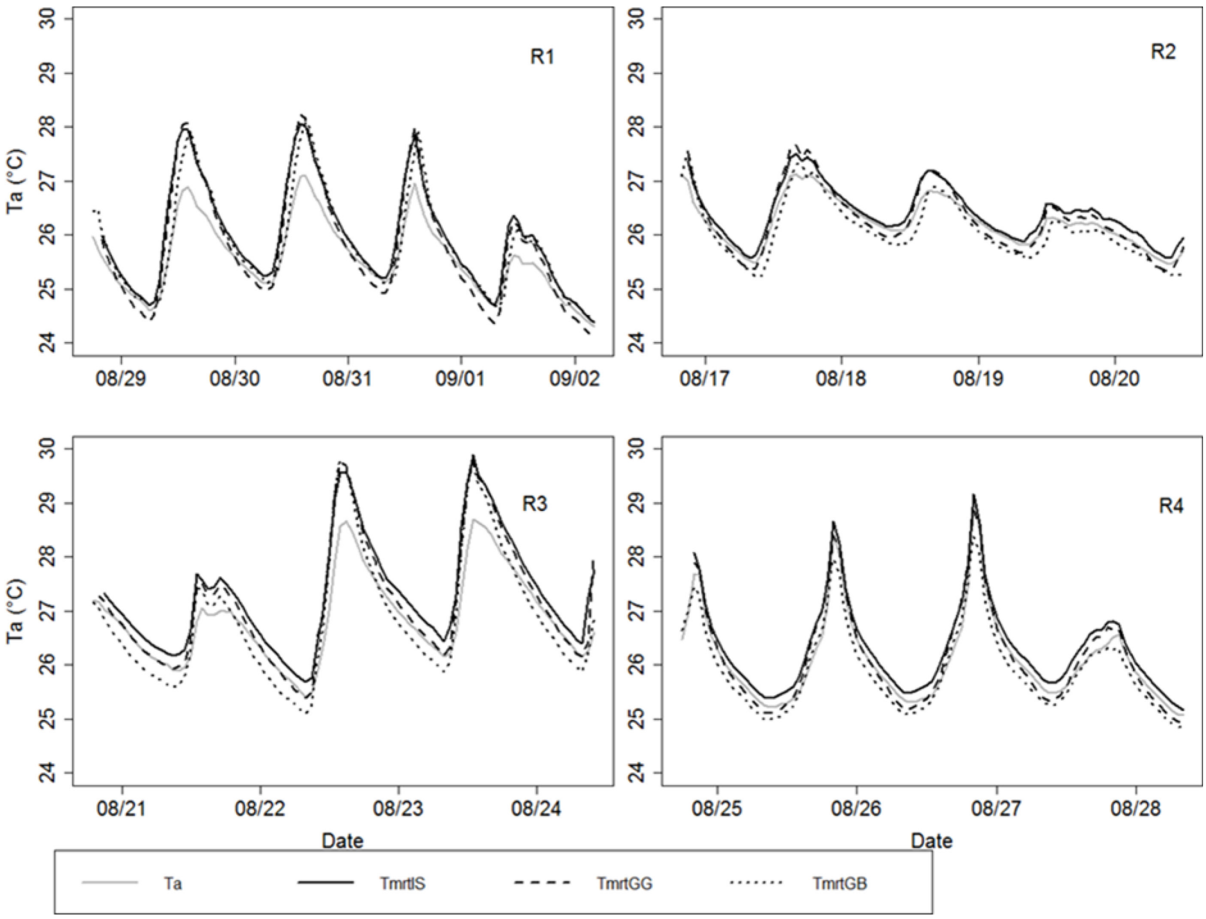


Figure 2.3 Comparison of Ta and three different methods of obtaining Tmrt in the four rooms (R1-4); TmrtGB=Tmrt black globe; TmrtGG=Tmrt grey globe; TmrtIS=Tmrt from the integral radiation measurement

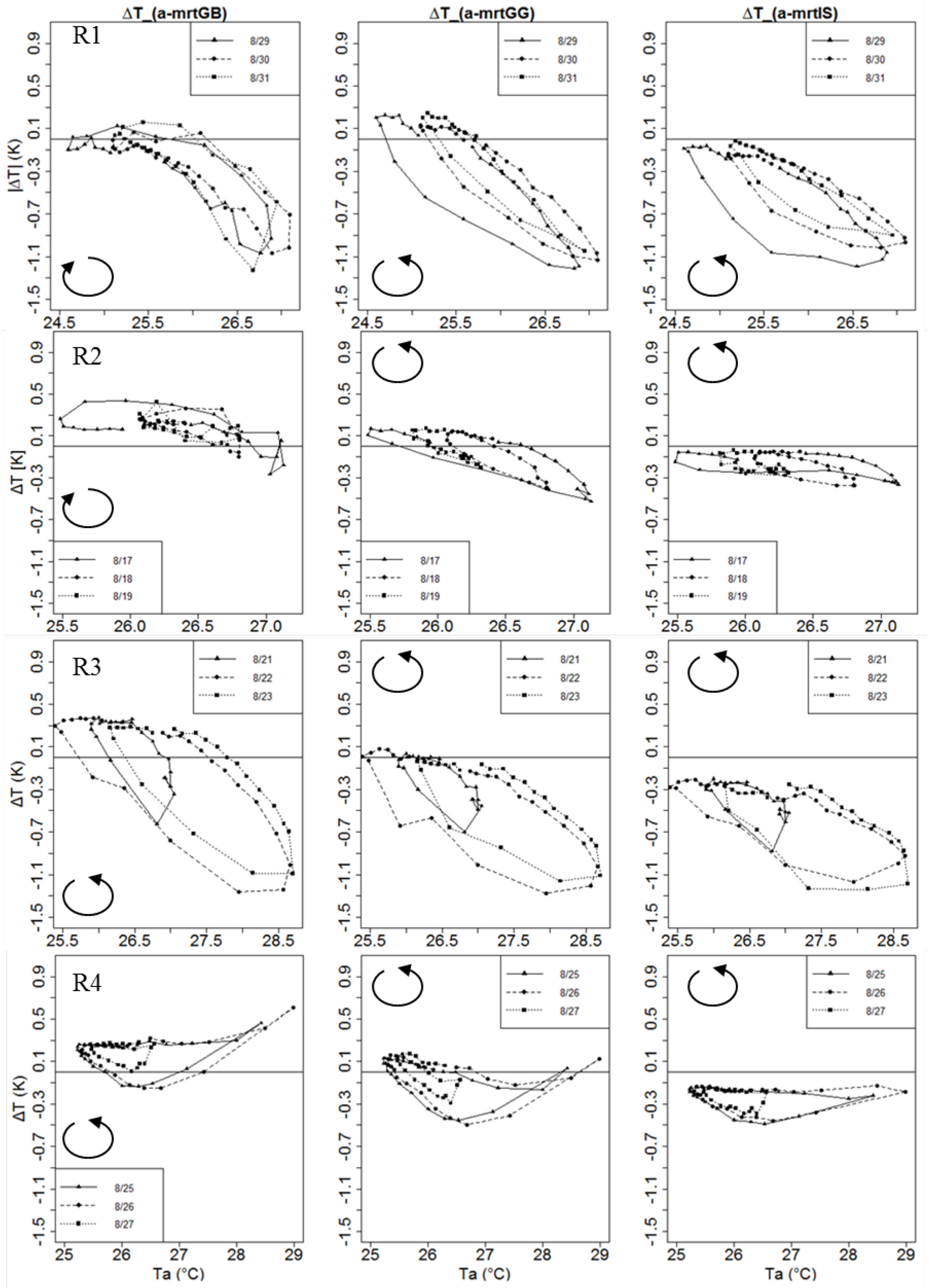
2.3.2 Temporal differences between Ta and Tmrt

Figure 2.4 shows the difference between Ta and Tmrt ($\Delta T_{a-mrtGB}$, $\Delta T_{a-mrtGG}$and $\Delta T_{a-mrtIS}$). All three show a hysteresis effect with, on average, higher Tmrt compared to Ta. During low temperatures, the disparities are approximately zero or positive, but with rising temperatures in the morning hours, Tmrt increases more than Ta. The greatest difference (-1.2 K) occurs at the highest Ta value but at different times ($\Delta T_{a-mrtGB}$ 3 pm, $\Delta T_{a-mrtGG}$ 1 pm, $\Delta T_{a-mrtIS}$ 12 am). Decreasing temperatures in the evening and night correspond to decreasing differences. The disparities between Tmrt and Ta in R2 are lower compared to R1. $\Delta T_{a-mrtGB}$ is almost positive throughout the whole period, whereas $\Delta T_{a-mrtGG}$ changes between positive and negative, and $\Delta T_{a-mrtIS}$ is only negative. The greatest difference (-0.5K) occurs at the highest air temperature of about 27.3°C (2 pm; $\Delta T_{a-mrtGG}$). Most of the differences in R2 lay within the measurement uncertainty of Ta (±0.5°C) and are hence not usable for the interpretation of the results.

The results in R3 show a hysteresis effect with, on average, higher Tmrt values compared to Ta (Fig 2.4). Smaller differences during night-time and larger differences during the day (max -1.28 K; 11 am) are followed by a lower-amplitude decrease during afternoon and evening. Similar to R1, $\Delta T_{a-mrtGB}$ varies between positive and negative values, whereas $\Delta T_{a-mrtIS}$ is exclusively negative. The differences between Ta and Tmrt in R4 show a different pattern compared to the other rooms but with, on average, higher Tmrt than Ta values (Fig 2.4). The maximum difference occurs at moderate temperatures within $\Delta T_{a-mrtGG}$ and $\Delta T_{a-mrtIS}$ (-0.5 K, 4 pm). $\Delta T_{a-mrtGB}$ has a maximum difference of +0.6 K (6 pm) at the peak temperature. The results of all rooms do not indicate a large difference between the different Tmrt and Ta values at low and medium temperatures. However, the analysis showed larger differences at higher air temperatures.

(next page)

Figure 2.4 Differences between Ta and ΔT_{a-mrt}; the three different graphs show the difference between Ta and the different Tmrt values in the four rooms (R1-4); the hysteresis rotation is indicated by arrows


ΔT_(a-mrtGB)
ΔT_(a-mrtGG)
ΔT_(a-mrtIS)
R1
R2
R3
R4
8/29
8/30
8/31
8/17
8/18
8/19
8/21
8/22
8/23
8/25
8/26
8/27
|ΔT| (K)
ΔT [K]
ΔT (K)
Ta (°C)

2.3.2 Investigation of possible causes for the differences between Ta and Tmrt

2.3.2.1 Surface temperatures of the surrounding walls

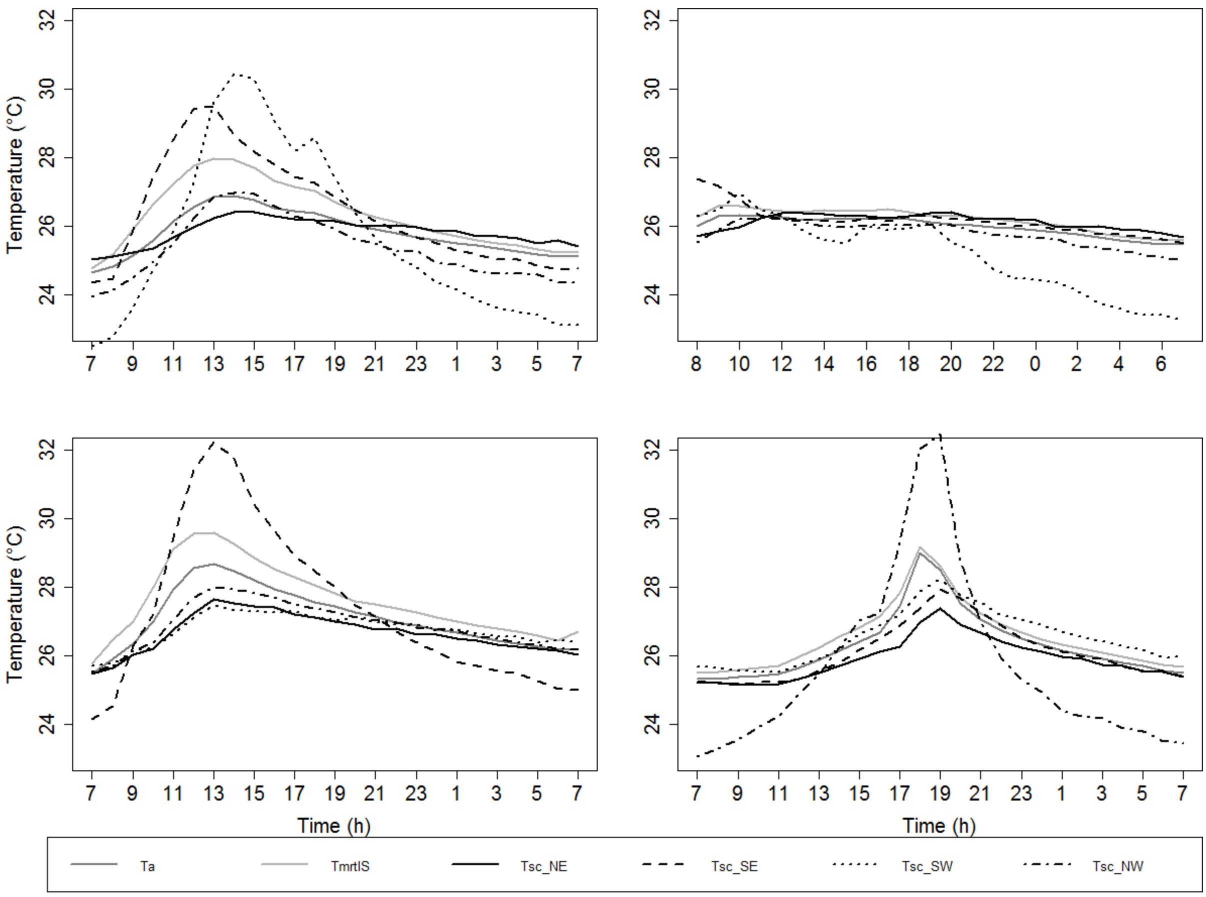


Figure 2.5 Comparison of surface temperatures derived with a contact thermometer (Tsc) of all surrounding walls in each room (R1-4) using air and mean radiant temperature (TmrtIS)

The results of the investigation of Tsc (three point measurement with a contact thermometer) are presented in Figure 2.5. The Tsc of the window walls in all rooms (except R2) exceed the Ta and Tmrt during their daily maxima. The highest values in R1 are reached at 2 pm (30.4°C), in R3 at 1 pm (32.2°C) and in R4 at 7 pm (32.5°C). Additionally, they show the highest daily temperature amplitudes compared to the other walls (R1 8K, R3 8.1K, R4 9.4K). The particular opposite walls show minor daily temperature maxima (R1 26.4°C, R3 28°C, R4 27.9°C) and lower daily temperature amplitudes (R1 1.4K, R3 2.5K, R4 2.1K). The Tsc values of R2 differ considerably less compared to the other rooms. The window wall (SW) shows its highest value at 10 am (27.1°C) but has a noticeable lower daily temperature amplitude (3.7 K) compared to the window walls of the other rooms. The particular opposite wall (NE) has the highest temperature at 8 pm (26.4°C) and a very small daily temperature amplitude of 0.7 K. In summary, the results indicate notable differences between the surrounding walls in the rooms. Because of the simpler investigation of Tsc, possible inaccuracies cannot be excluded, and hence a more detailed surface temperature investigation using TIR (Tst) are compared with Tsc.

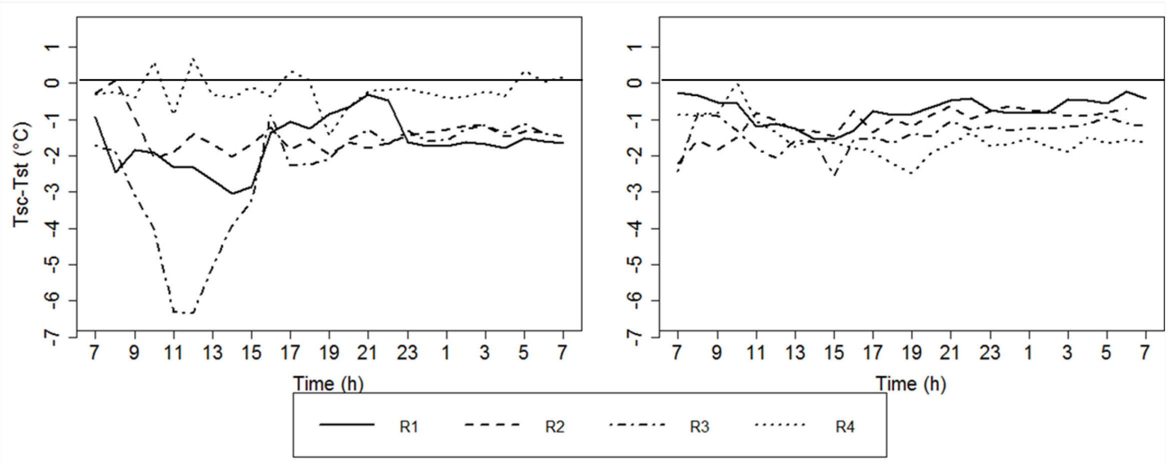


Figure 2.6 Differences between Tsc and Tst in all four rooms; left: window side; right: opposite walls; Tcs is derived using a contact thermometer at three points per wall; the Tst values were recorded with a thermal infrared camera

Figure 2.6 indicates the differences between Tsc and Tst at the windows and their opposite walls. Tst is almost always higher than Tsc. The greatest differences appear in R1 at 2 pm (-3.1 K) and in R3 from 11 am until 12 am (-6.3 K) on the window side. The differences in R2 (11 am; -2.1 K) and R4 (7pm; -1.4 K) are minor. The differences at the opposite walls are more consistent throughout the day, with no comparable peaks. Figure 2.7 illustrates the temperature distribution of Tst at 11 am and 2 pm and at night at 11 pm. The times were chosen to analyse the period were the highest differences between the surface temperatures and Tmrt occur and to compare these daytime peaks with values measured during night. The results are presented in probability densities, which represent the relative frequencies divided by the interval width of 0.2K. In general, the Tst values of the window walls show a markedly broader band at all presented times compared to the Tst values of the opposite walls. R1 and R3 show low probability densities, but the greatest temperature amplitude (>10 K) during sunny conditions (2 pm) and the opposite behaviour at 11 am and 11 pm. The opposite walls display higher probability densities throughout the day and lower temperature amplitudes at all times of the day. R3 and R4 have the greatest dissimilarities in the room. R3 has very low probability densities and high temperature amplitudes at the window wall. The NW wall is characterised by high probability densities and low amplitudes. R4 has the same pattern, but Tst at 2 pm shows higher temperatures at the window than at the SE wall. An additional Wilcoxon-Test indicates that the described differences between the window and the opposite walls in all rooms are significant (99% confidence interval).

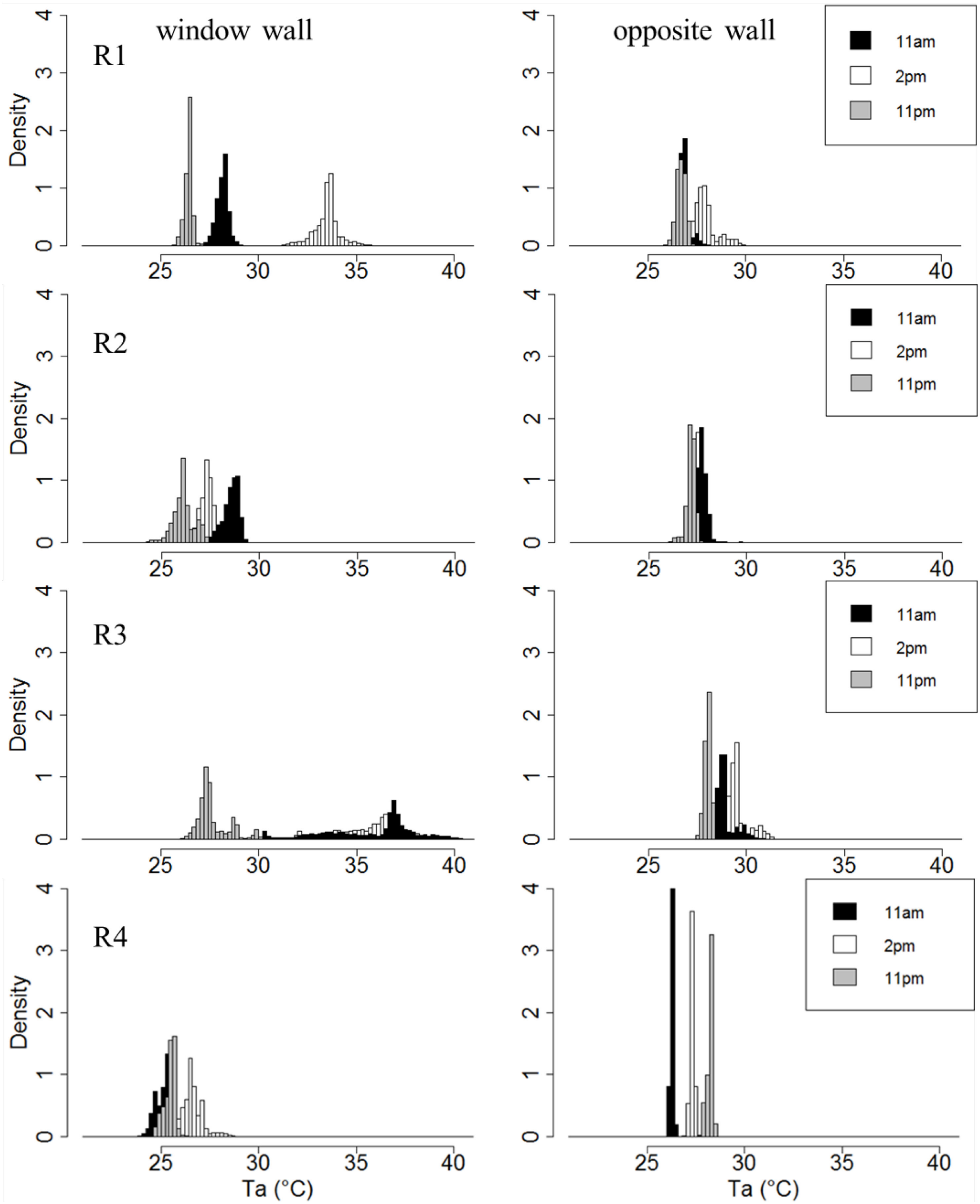


Figure 2.7 Tst distributions of the window and its opposite wall in the rooms (based on thermal infrared images) at 11 am, 2 pm and 11 pm ; the Tst values are plotted in probability densities

2.3.2.2 The influence of short and long wave radiation

The following analysis of $\Delta T_{a-mrtIS}$ compared to short and long wave radiation was conducted to investigate further causes of differences between Ta and Tmrt. Table 4 specifies the correlation between $\Delta T_{a-mrtIS}$ and short wave radiation and $\Delta T_{a-mrtIS}$ and long wave radiation at the window and its opposite wall. R1 and R3 show strong and very strong correlations at the window sides at both ranges of wavelengths. Short wave radiation, however, shows a weak correlation at the opposite walls. Furthermore, indicated by R^2 values, the table shows the influence of solar radiation, represented by short wave radiation, on $\Delta T_{a-mrtIS}$. In R1, the variance of Ta and Tmrt at the window wall (opposite wall) can be explained by 82% (30%), whereas in R4 just 37% (20%) of the variance can be explained. Figure 2.8 displays the results of the regression analysis of the $\Delta T_{a-mrtIS}$ and the sum of short and long wave radiation (RAD) at the window (left) and the opposite wall (right) in all four rooms. R1 and R3 show a very strong correlations at the window side (correlation coefficient 0.91 and 0.93, respectively), whereas R2 and R4 show a strong and middle correlation (0.73 and 0.50, respectively). The opposite walls show lower correlation coefficients compared to the window walls. R1 and R3 have a strong correlation (0.82 and 0.79, respectively), and R2 and R4 show middle (0.58) and weak (0.25) correlations, respectively.

Table 2.4 Correlation coefficients and R squared values for the comparison of $\Delta T_{a-mrtIS}$ and short (SW) and long wave (LW) radiation; W represents the window and O the opposite wall in the study rooms (R1-4); r = Pearsons correlation coefficient; R^2= coefficient of determination; $\Delta T_{a-mrtIS}$ is presented as $|\Delta T_{a-mrtIS}|$

	SW_W		**SW_O**		**LW_W**		**LW_O**	
	r	R^2	r	R^2	r	R^2	r	R^2
R1	0.91^{*}	0.82^{***}	0.55^{*}	0.30^{***}	0.81^{*}	0.65^{***}	0.71^{*}	0.51^{***}
R2	0.80^{*}	0.64^{***}	0.19^{ns}	0.00^{ns}	0.65^{*}	0.43^{***}	0.55^{*}	0.30^{***}
R3	0.72^{*}	0.51^{***}	0.44^{*}	0.18^{***}	0.88^{*}	0.78^{***}	0.74^{*}	0.56^{***}
R4	0.61^{*}	0.37^{***}	0.44^{*}	0.20^{***}	0.37^{*}	0.14^{***}	0.19^{ns}	0.04^{ns}

*95% confidence interval; ***99.9% confidence interval; ^{ns} not significant

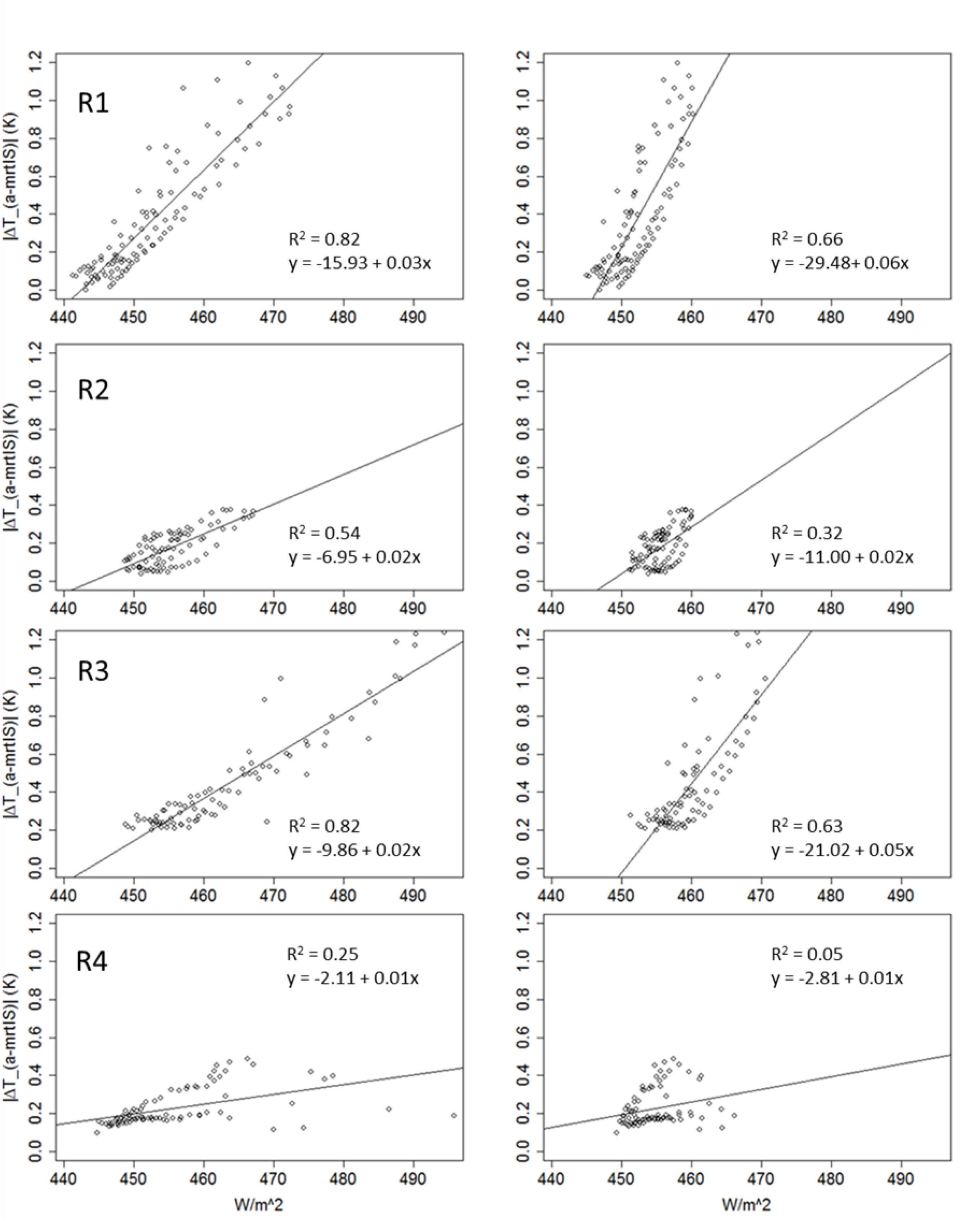


Figure 2.8 Correlation of $\Delta T_{a-mrtIS}$ and the sum of short and long wave radiation (RAD) determined from the detailed integral radiation measurement in the four rooms (R1-4); left: window wall; right: opposite wall; $\Delta T_{a-mrtIS}$ is presented as $|\Delta T_{a-mrtIS}|$

2.4 Discussion

With regard to the comparison of different methods obtaining Tmrt, the results of this work indicate corresponding daily cycles of all Tmrt values per room and similar daily maximums at high air temperatures. Days with changing outdoor conditions and cloud cover increasing to 6/8 (e.g., 18.08 until 20.08, 22.08, 28.08), however, show disparities between Tmrt and during low temperatures during the night. On average, the black globe thermometer (TmrtGB) has more inertia over time but shows the highest daily amplitudes, meaning the lowest values during the night and high values during the day (Fig 2.4. $\Delta T_{a-mrtGB}$). Kántor and Unger (2011) explained the longer response time as a result of the size of the globe. It takes up to 20 minutes to reach equilibrium, and fast changing conditions, as occur in the morning, become uncertain. Additionally, the black globe overestimates the absorption in the short wave range, which may explain the highest daily amplitude. TmrtGG shows a reduced daily amplitude and a shorter response time in the morning because of the reduced size and short-wave absorption of the globe (Kuehn et al. 1970). The reduced size affects the globe's temperature through increased convective heat exchange and a reduced influence of radiation. No difference was found regarding the different colours of the grey globes. The differences between Tmrt indoors, based on different measurement methods, are minor (Tab 2.2). The grey and black globe thermometers give good approximations of the integral radiation measurements in indoor conditions.

The analyses of the reasons of ΔT_{a-mrt} indicate room characteristics as well as solar radiation as the main drivers. This finding corresponds with the results of Mavrogianni et al. (2012), who reported that a great variation of air temperatures within dwellings depends on the building material, floor level and exposition of the room. R1 and R3 show a hysteresis effect which implies that the decreasing differences during late hours not only depend on the current state, but also on the past influencing factors and hence on the increasing Ta and Tmrt during the morning. R1 and R3 consist of a high percentage of window surfaces and are SW and SE exposed, respectively. The rooms heat up because of direct sunlight during times with high radiation intensities. The low values of ΔT_{a-mrt} in R2 can be traced back to cloudy conditions during the measurements. According to the results of Lindberg et al. (2014), cloudiness reduces global radiation and hence the direct radiation beam into the rooms. As a consequence, Tmrt decreases and approaches the values of Ta. Additionally, the direct heating of the room by direct radiation absorbed by floor and walls is strongly reduced compared to R1 and R3, where autochthonal weather conditions were observed. Despite the same exposition of R2 compared to R1, the window surface is smaller and the SE wall is made of concrete, whereas R1 has partially opaque glass. R4 is a NW exposed room with a smaller window and hence receives less direct sunlight during high exposure rates. This effect can be seen in the belated air temperature peak at 6pm. Furthermore, it has to be considered that Ta is one of the input variables in calculating TmrtGB and TmrtGG (equation 2). Through the consideration of the measurement accuracy of Ta (± 0.5 K) it can be assumed, that the small differences of TmrtGB and TmrtGG to Ta in R2 and R4 may be within the uncertainty of Ta measurements and thus not significant, whereas the results of R1 and R3 are clearly outside of these threshold. Additionally, an influence from the floor level was identified. The mean value of Ta shows the highest values in R3 and R4 (second floor) and the lowest values in R1 (ground floor). Whereas the differences in the mean Ta are marginal (1 K), the maximum Ta values confirm the influence with higher disparities between the floors (1.9 K) as seen in Table 2.2.

On average, the differences between Ta and Tmrt are negligible. The general assumption that they are equal can be made at first sight for indoor climates. Nevertheless, the study indicates that there are differences in rooms with a high percentage of window areas and SW or SE exposed glass facades. To investigate the reasons for this alteration, the correlations of $\Delta T_{a-mrtIS}$ and short and long wave radiation and the distribution of surface temperatures were analysed.

The 24 h analyses of the surface temperatures Tsc and Tst (Fig 2.5 and 2.7) indicate substantial differences between the surrounding walls in contrast to the assumptions that they are rather uniform (VDI 2008, Kántor & Unger 2011). Tsc underestimates the surface temperatures and is not sufficient for a detailed analysis (Fig 2.6). The comparison of Figure 2.4 and 2.7 suggests that the differences between Ta and Tmrt are influenced by the variable surface temperatures. The SE and SW side of R1 have the highest temperatures when direct sunlight hits the walls over a period of 9 hours. Tst shows a high temperature variance during the same time compared to the early and late hours of the day (Fig 2.7). As shown by Frieß (2002), the higher surface temperatures of a window façade can be explained by heat conduction through a window, which is generally higher than through walls made of concrete. This result agrees with the difference between Ta and Tmrt, which increases at midday and reaches its maximum almost simultaneously with the highest Tst.

Analyses regarding the influence of radiation on $\Delta T_{a-mrtIS}$ reveal that RAD has a great influence, especially in rooms with large window areas and SW exposition (R1 and R3). R4, in contrast, shows almost no difference between Ta and Tmrt, even though Tst of the window wall is considerably higher. This result suggests that the exposition and the intensity of direct solar radiation entering the room, as well as the duration of room exposure, is a major driving factor for Tmrt. The window wall of R4 is NW exposed and receives direct solar radiation with a lower exposure rate and over a shorter time span of 4 hours. This result agrees with the regression analysis, which indicates just a lower explanation of $\Delta T_{a-mrtIS}$ through RAD. During the measurement period in R2, no autochthonal weather conditions were given because of increasing cloud cover over the day. As a consequence, less direct solar radiation entered the room, and Tmrt was almost equal to Ta (Lindberg et al. 2014). Keeping in mind that R1 and R2 are of the same exposition and size, the results confirm the previous findings that ΔT_{a-mrt} is negligible as long as no or only a small amount of direct solar radiation enters the room.

By splitting RAD into short- and long wave radiation (Tab 2.3) a bigger influence of short wave radiation on $\Delta T_{a-mrtIS}$ is visible at the window walls. This is consistent with the physical conditions, whereas only short wave radiation will directly enter a room and long-wave radiation is completely absorbed at the outdoor side of the window (Frieß 2002). R2 and R4 show again diminished results due to exposition and outdoor atmospheric conditions. At the opposite walls, the influence of long wave radiation exceeds short wave radiation but explains less variance of $\Delta T_{a-mrtIS}$ compared to SW radiation at the window wall. Analyzing just long wave radiation, the correlation at the window wall is higher because of the fact that heat conduction through glass facades is higher than through walls. In summary, the results indicate that the differences between

Ta and Tmrt are mainly derived through the amount of short- and long wave radiation entering a room at the exposed walls.

2.5 Conclusions

A comprehensive measurement campaign of indoor climate parameters was conducted within four rooms in one building in Berlin during August 2013. The present study was designed to investigate the relationship between Ta and Tmrt and to examine possible influences on them under warm conditions. The difference between the two parameters is negligible under moderate outdoor conditions, which is consistent with earlier studies. Ta and Tmrt, however, showed differences at air temperatures above average in rooms with SE and SW exposed window walls. The surrounding walls differed in surface temperatures, and the radiation fluxes were not uniform. The size and exposition of the window and the intensity and duration of direct solar radiation entering a room or hitting the surface were identified as the driving factors of the difference between Ta and Tmrt. Some caution is needed when interpreting the findings. First, the results are only valid for summer conditions, with warm outdoor temperatures and intense solar radiation. During winter, energy fluxes and the intensity of solar radiation are different and must be investigated separately. Second, only one building was analysed. The presented detailed case study indicated the influencing variables, which differ depending on the dwelling construction. The results are only valid for modern constructions with an above average percentage of window surfaces. To improve the study, different buildings with varying materials should be analysed. In a next step, a dynamical simulation, covering the same period as the instrumental measurement will be conducted to reappraise the results of this study and to verify the findings.

Prospective studies investigating indoor climates during high outdoor temperatures or even heat waves are recommended to examine Tmrt. Tmrt is required to calculate thermal indices that are widely used in heat stress studies. By equalising Tmrt and Ta, indoor heat stress may be underestimated, and the wrong conclusion regarding human health may be obtained. Hence, further investigations regarding the sensitivity of thermal indices are needed. The use of a globe thermometer, a practical alternative to complex measurements, was shown.

Acknowledgements

We would like to thank the German research foundation (DFG) for funding Research Unit 1736 'Urban Climate and Heat stress in mid-latitude cities in view of climate change (UCaHS)' (EN138/21-1 and SCHE 750/9-1). We also wish to thank the members of the research group for their enriching discussion as well as Phillip Schuster for his support with data collecting.

CHAPTER 3: ASSESSMENT OF INDOOR HEAT STRESS VARIABILITY IN SUMMER AND DURING HEAT WARNINGS: A CASE STUDY USING THE UTCI IN BERLIN, GERMANY

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Published in:

International Journal of Biometeorology. Students and New Professionals 2015: 1-14

Abstract

Humans spend most of their time in confined spaces and are hence primarily exposed to the direct influence of indoor climate. The Universal Thermal Climate Index (UTCI) was obtained in 31 rooms (eight buildings) in Berlin, Germany during summer 2013 and 2014. The indoor UTCI was determined from measurements of both air temperature and relative humidity and from data of mean radiant temperature and air velocity, which were either measured or modeled. The associated outdoor UTCI was obtained through facade measurements of air temperature and relative humidity, simulation of mean radiant temperature and wind data from a central weather station. The results show that all rooms experienced heat stress according to UTCI levels, especially during heat waves.

Indoor UTCI varied up to 6.6 K within the city and up to 7 K within on building. Heat stress either during day or at night occurred on 35 % of all days. By comparing the day and night thermal loads we identified maximum values above the 32 °C threshold for strong heat stress during the nighttime. Outdoor UTCI based on facade measurements provided no better explanation of indoor UTCI variability than the central weather station. In contrast, we found a stronger relationship of outdoor air temperature and indoor air temperature. Building characteristics, such as the floor level or window area, influenced indoor heat stress ambiguously. We conclude that indoor heat stress is a major hazard, and more effort toward understanding the causes and creating effective countermeasures is needed.

Key words: Indoor climate, heat stress, UTCI, indoor measurements

3.1. Introduction

Heat stress is a serious risk to humans, especially in cities where the global increase in air temperature (Ta) is amplified by urban structures (Matzarakis & Endler 2010). A significant increase in mortality due to heat stress has been shown by McMichael and Haines (1997), Smoyer et al. (2000), Michelozzi et al. (2009a), D'Ippoliti et al. (2010), Gabriel and Endlicher (2011), Ye et al. (2012), Almeida et al. (2013). Analyses regarding heat stress and morbidity (McGeehin & Mirabelli 2001, Monteiro et al. 2013, Scherber et al. 2013), as well as impacts on human well-being (Kjellstrom & McMichael 2013), have been conducted. Heat stress and work performance also have a strong interrelationship (Witterseh et al. 2004, Lundgren et al. 2013),

However, only a limited number of studies examined the role of indoor climates in hazardous atmospheric conditions (Pfafferott & Becker 2008). People in industrialized countries spend on average 90 % of the day in confined spaces; hence, the assessment of indoor heat stress is an important issue. The influence of outdoor climate on indoor climate, especially during heat stress events, has been well investigated (Nguyen et al. 2014, Quinn et al. 2014). Indoor Ta is mainly influenced by outdoor Ta, but its diurnal course is inhibited due to the physical characteristics of the building (Höppe 1993). Furthermore, thermal radiative fluxes within enclosed environments have a higher importance than solar radiation. However, when direct solar radiation enters a room through the windows, the additional thermal load needs to be considered (La Gennusa et al. 2005). Studies by for example Höppe (1993) and Melikov et al. (2013) indicate that air velocity (v) influences the convective heat transfer and therefore improves the thermal sensation, especially at high room temperatures and humidity levels. Based on these results and those of further studies, it is evident that for the assessment and description of indoor heat stress, the meteorological parameters Ta, relative humidity (RH), v and mean radiant temperature (Tmrt) should be considered.

Thermal indices, such as the recently developed UTCI (Jendritzky et al. 2012) that is used in this study, achieve this requirement. The UTCI is based on a multi-node model of human heat transfer and temperature regulation (Fiala et al. 2012). Furthermore, an up-to-date clothing model takes into account the typical dressing behaviors in different thermal conditions and it is further representative of European and North American urban populations in outdoor spaces (Havenith et al. 2012). Bröde et al. (2012) provided a detailed description of the operational procedure to calculate the UTCI.

Indoor thermal conditions in urban areas have been assessed by for example Mirzaei et al. (2012) and Beizaee et al. (2013) but they only focus on Ta as the describing or forcing variable of indoor thermal conditions. Furthermore, these studies and others (Nguyen et al. 2014, Quinn et al. 2014) used central weather stations or simulations to describe the outdoor conditions. Hence, the urban spatial variability is not considered in their studies. Fenner et al. (2014) found significant spatial and temporal differences in outdoor Ta during heat waves in Berlin, and it is therefore likely that indoor climate differs within the urban area. Langner et al. (2013) used the UTCI for the assessment of indoor climate but only measured Ta and RH and did further not consider the outdoor climate.

Our chief objective was to examine the spatial and temporal variability of indoor heat stress in different buildings in Berlin, Germany. Based on the data of a detailed measurement system of indoor and outdoor climate, distributed over the city during summer 2013 and 2014, we calculate the UTCI to consider the main meteorological parameters Ta, RH, Tmrt and v. Furthermore, we examined heat-warning periods to estimate the maximal thermal load during the day and night. In a second step, the main driving factors of outdoor climate and building characteristics are analyzed. For the outdoor conditions, we calculated the UTCI based on on-site data to consider local climate variations in urban areas. To evaluate the results, we also used data from a central weather station. The building characteristics of floor level, window size and year of construction are considered to estimate differences between and within the observed buildings.

3.2. Methodology

To assess the variability of indoor heat stress, measurements were executed in eight different buildings (Fig. 3.1, Table 3.1) within 31 rooms, and outdoor data were measured at six different sites. Most measurements began in June 2013 and are ongoing. For this study, the 2013 and 2014 summer periods from the 1st of June to the 31st of August (184 days) were used. Due to the heterogenic urban structure of Berlin, we aimed to cover the most prevailing building types, constructed in various years. Due to the innovations of the UTCI (Jendritzky et al. 2012) and the need for a standardized application to compare indoor and outdoor conditions, the results are presented using the UTCI, even though the index was originally developed for outdoor conditions. The UTCI calculations were conducted with the software program RayMan 1.2 (available from http://www.mif.uni-freiburg.de/rayman/intro.htm) using the input parameters Ta, RH, v and Tmrt, as well as geographical data of Berlin (Matzarakis et al. 2007, Matzarakis et al. 2010). Measured levels of v were mainly below the range of validity of 0.5 m/s at a level of 10 m above ground for the use of the regression function to calculate UTCI (Bröde et al. 2012). Hence, values below this threshold, as well as v values in rooms where no measurements were conducted, were set to 0.3 m/s at the level of a person's body. Furthermore, a metabolic heat production of 135 W/m^2 was assumed for all UTCI calculations. The analysis was conducted using the software program R Version 2.15.1 (RCoreTeam 2012), and all measurements were registered in Central European Time (CET).

The analysis of the intra-urban and temporal variability of indoor heat stress is based on five study sites OF1, OF2, SC, RH1 and RH2 (Table 3.1). At the HO, H1 and H2 sites only two rooms were equipped with the measurement devices. Hence, no heat stress variability within the buildings can be described, and the sites are solely used for the indoor-outdoor comparison. Results relating indoor to outdoor climate are thus based on the study sites SC, RH1, RH2, HO, H1 and H2 due to data availability.

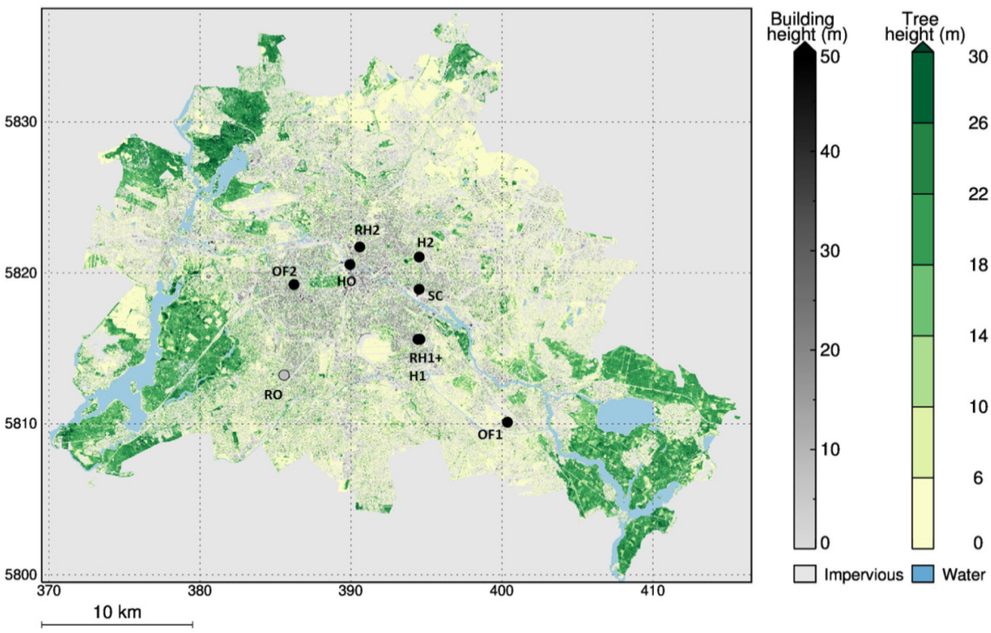


Figure 3.1 Map of Berlin including the eight study sites (black) and the reference station RO (grey). Data source: http://www.stadtentwicklung.berlin.de/umwelt/umweltatlas/ei610.htm

3.2.1 Indoor study design

The instrumental setup for the indoor measurements varies between the study sites (Table 3.1). In office 1 (OF1) and office 2 (OF2), as well as in the private flat 1 (H1), Ta, RH, v and Tmrt were measured. At the remaining sites (school (SC+SC*), retirement home 1 (RH1) and retirement home 2 (RH2), hospital (HO) and the private flat 2 (H2)), only Ta and RH could be measured. At these study sites, the Tmrt was set to Ta, an assumption which was already used and explained in previous studies (Kántor & Unger 2011). To measure Ta and RH, each room was equipped with two Testo 174H loggers (accuracy of ±0.5 °C and ±3 %RH, respectively). V was derived by one PCE-009 hot wire anemometer per room (accuracy of ±0.5 %), and Tmrt was measured by the use of one black globe thermometer (KIMO) per room (accuracy of ±0.5 °C; 150 mm in diameter; 0.4 mm thickness). The use of a globe thermometer gives a good approximation of the detailed and extensive integral radiation measurement (Bedford & Warner 1934, Kuehn et al. 1970, Walikewitz et al. 2015b). The sensors were fixed at a height of approximately 1.1 m above the ground, corresponding to the average height of the center of gravity for adults. The investigated rooms in each building are located at different floor levels but are equal in size and orientation of the windows (southwest). One room per side is northeast oriented to estimate the influence of direct solar radiation (indicated by N). Study side SC differs due to a lightweight construction extension of the building at the top floor with different window areas and orientation (indicated by *) compared to the solid stone construction from 1909.

To estimate the average conditions per room, the placement of sensors at locations where they may be influenced by direct solar radiation or heating installations was avoided. All data were recorded at 5-minute intervals and then aggregated to mean hourly/daily values only when all data on a given hour/day were available.

Figure 3.2 Overview of the outdoor facades of the five study sites used for the indoor climate analysis

Table 3.1 Overview of the measurement sites as well as the indoor/outdoor data acquisition; air temperature (Ta), relative humidity (RH), air velocity (v), mean radiant temperature (Tmrt); in buildings where only Ta and RH was measured, Tmrt was set be equal to Ta and v was ✓t to be 0.3 m/s; indicates for which part of the analysis the data are used; RO=reference station; *partly enlarged in 2006; ** reconstructed in 1950 after the second world war; *** windows within a room have the same size

	overview								**indoor**		**outdoor**	**data usage**	
site	**abbreviation**	**year of construction**	**geographic coordinates**	**total size of windows (m^2) per room**	**room size (m^2) /volume (m^3)**	**orientation of the rooms (windows)**	**floor levels**	**wall material**	**number of rooms/start**	**measured values**	**measured floor**	**indoor**	**outdoor comparison**
Office 1	**OF1**	2003	13.534373 52.432088	19.5	50.1/97	3 southwest 1 northeast	5	concrete	4 06/2013	Ta, RH, v, Tmrt	no measurements	✓	
Office 2	**OF2**	1962	13.323401 52.511305	8.4	19.4/62	4 southwest 1 northeast	10	concrete	5 06/2013	Ta, RH v, Tmrt	no measurements	✓	
School	**SC** **SC***	1909 2006*	13.44554 52.510148	8.2/12.2*	52.2/208 70.6/211*	4 southwest 3 southeast*	4	brick concrete*	4/3* 06/2013	Ta, Tmrt=Ta RH, v=0.3 m/s	1st, 4th	✓	✓
Retirement home 1	**RH1**	2004	13.447388 52.480398	5.3	17.7/44	4southwest 1 northeast	5	concrete	5 06/2013	Ta, Tmrt=Ta RH, v=0.3 m/s	1st	✓	✓
Retirement home 2	**RH2**	1993	13.386747 52.534539	3.3	21.5/55	3southwest 1 northeast	5	concrete	4 06/2013	Ta, Tmrt=Ta RH, v=0.3 m/s	3rd, 5th	✓	✓
Hospital	**HO**	1900 1950**	13.377579 52.523924	3.4	31.8/111.3	1southwest	5	brick	1 05/2014	Ta,Tmrt=Ta RH, v=0.3 m/s	3rd		✓
Private flat 1	**H1**	1910	13.445280 52.480403	3.2	24.6/73.8	1southwest 1 northeast	5	brick	2 10/2013	Ta, RH v, Tmrt	data from side RH1		✓
Private flat 2	**H2**	1920	13.444979 52.529375	3.3	35.2/112.6	1southwest 1 northeast	5	brick	2 06/2014	Ta, RH, Tmrt, v=0.3 m/s	3rd floor		✓

3.2.3 Outdoor study design

The outdoor observations consisted of Ta and RH sensors (DK390 HumiLog GP "rugged", EU-325 ±0.3 °C and RFT-325 ±2 %) at six sites (Table 3.1) that are ventilated when sunlit by means of solar panels. Wind speed and global radiation, which were used for the calculation of outdoor Tmrt and UTCI, were observed only at one reference station in Berlin, Rothenburgstraße (RO; 52.4572 N, 13.3158 E; 47m amsl) at roof level (20 m) with a cup anemometer and a star pyranometer (see Fenner et al. (2014)).

We simulated Tmrt for each site with the radiation model SOLWEIG 2014a (Lindberg et al. 2008) to obtain Tmrt values that should be representative of the outdoor conditions in the environment near the analyzed building sites. Therefore, we used digital surface models (DSM) of vegetation and buildings provided by Senate Department for Urban Development and the Environment, Berlin (2014). For each site, we defined a domain of 100 m × 100 m around the indoor station with a resolution of 5 m. Meteorological input was derived from on-site observations of relative humidity and air temperature together with off-site observations of wind speed and global radiation from RO. The simulated Tmrt of each domain was then averaged to a spatially median value for each hour, whereas roof areas were excluded. In the SOLWEIG simulation, we applied the following parameters: 0.25 as the fraction of the canopy DSM and 0.034 as the mean transmissivity according to Konarska et al. (2014), albedo=0.15, emissivity (walls)=0.9, emissivity (ground)=0.95, absorption (shortwave)=0.7, absorption (longwave)=0.9.

3.2.4 Heat waves

During the study period in 2013, three weather warning periods regarding outdoor heat stress were issued by the German weather service (DWD) and four in 2014. For a detailed description of the warning system of the DWD, see Koppe (2009). The first and the second period in 2013 lasted 3 days (18/06-20/06; 26/07-28/07), while the third one lasted 6 days (02/08-07/08). In 2014, the warning periods were shorter. The first one lasted three days (08/06-10/06), but the remaining three lasted only two days each (06/07-07/07; 19/07-20/07; 28/07-29/07). Heat warnings are divided into warning classes: Class 0 represents no heat warning, class 1 strong heat load and class 2 extreme heat load. All warning periods will be named heat waves (HW) in the following study and are numbered in ascending order based on their chronological appearance. The warning of one day is valid from 11am to 7pm. Heat stress levels regarding the UTCI are moderate heat stress (≥26 °C UTCI) and strong heat stress (≥32 °C UTCI).

3.3. Results

Table 3.2 presents the unequally distributed number of days with heat stress (UTCI ≥26 °C) at the different study sites in 2013 and 2014. In 2013, indoor heat stress occurred on 38.5 % of all days. The mean UTCI values of all rooms ranged from 23.1±1.4 °C to 29.9±3.3 °C. The maximum UTCI calculations varied between 27.3 °C and 39.6 °C, and the minimum UTCI data from 18.6 °C to 23.6 °C. In 2014, heat stress was documented on 29.6 % of all days. The mean UTCI varied between 22.3±1.3 °C and 27.9±3.4 °C, whereas the maximum values ranged from 27.6 °C to 37.0 °C and minimum between 18.2 °C and 21.7 °C. On average, the UTCI values were lower in 2014, but the moderate heat stress threshold (≥26 °C) was exceeded more frequently at some sites. All study sites experienced heat stress during the heat stress warning periods. The mean daily UTCI variability indoors (mean=0.56, max= 2.2, min= 0.3) was lower compared to outdoors (mean=9.78, max=17.5, min=4.3).

Table 3.2 Number of days (d) with mean indoor/outdoor UTCI ≥ 26°C (moderate heat stress level) per study side in 2013 and 2014; NA= missing daily data; percentage of days (%) of all measured data above 26 °C (NA not included); n=92 per year

	2013 indoor			**2014 indoor**			**2013 outdoor**			**2014 outdoor**		
	d	**%**	**NA**	**d**	**%**	**NA**	**d**	**%**	**NA**	**d**	**%**	**NA**
OF 1	58	77.3	17	52	56.5	0	-	-	-	-	-	-
OF 2	29	40.3	20	39	42.4	0	-	-	-	-	-	-
SC	15	22.1	21	33	35.9	0	14	18.4	16	16	17.4	5
RH 1	27	34.2	13	24	26.1	0	-	-	-	12	13.8	5
RH 2	17	18.5	0	30	34.5	5	18	19.6	0	17	19.5	5
HO	-	-	-	18	20.9	6	-	-	-	17	21.5	13
H 1	-	-	-	18	19.6	0	-	-	-	13	14.9	5
H 2	-	-	-	14	17.3	11	-	-	-	18	24.7	19
mean	**29.2**	**38.5**	**14.2**	**28.5**	**29.6**	**2.8**	**16.0**	**19.0**	**8.0**	**15.5**	**18.6**	**8.7**

3.3.1 Description of the spatial and temporal variability of indoor heat stress

The spatial and temporal heat stress variability of indoor UTCI among the different sites is large in both years (Fig. 3.3). Statistical analysis of variance shows that there is a significant effect of the study site on UTCI ($F(4,839)=50.6$, $p<0.05$). The mean daily variability of indoor UTCI within the city was 4.87 K in 2013 and 3.93 K in 2014. The spatial variability of each day during the heat waves is presented in Table 3.3.

Table 3.3 Mean UTCI variability (in K) for each day of the heat waves within the city

	day of the heat wave					
	1day	**2day**	**3day**	**4day**	**5day**	**6day**
1HW	6.62	3.52	2.24	-	-	-
2HW	5.14	5.08	5.85	-	-	-
3HW	4.95	4.95	5.36	5.20	4.88	4.66
4HW	2.24	2.32	2.01	-	-	-
5HW	2.62	2.23	-	-	-	-
6HW	3.92	4.06	-	-	-	
7HW	2.25	2.36	-	-	-	-

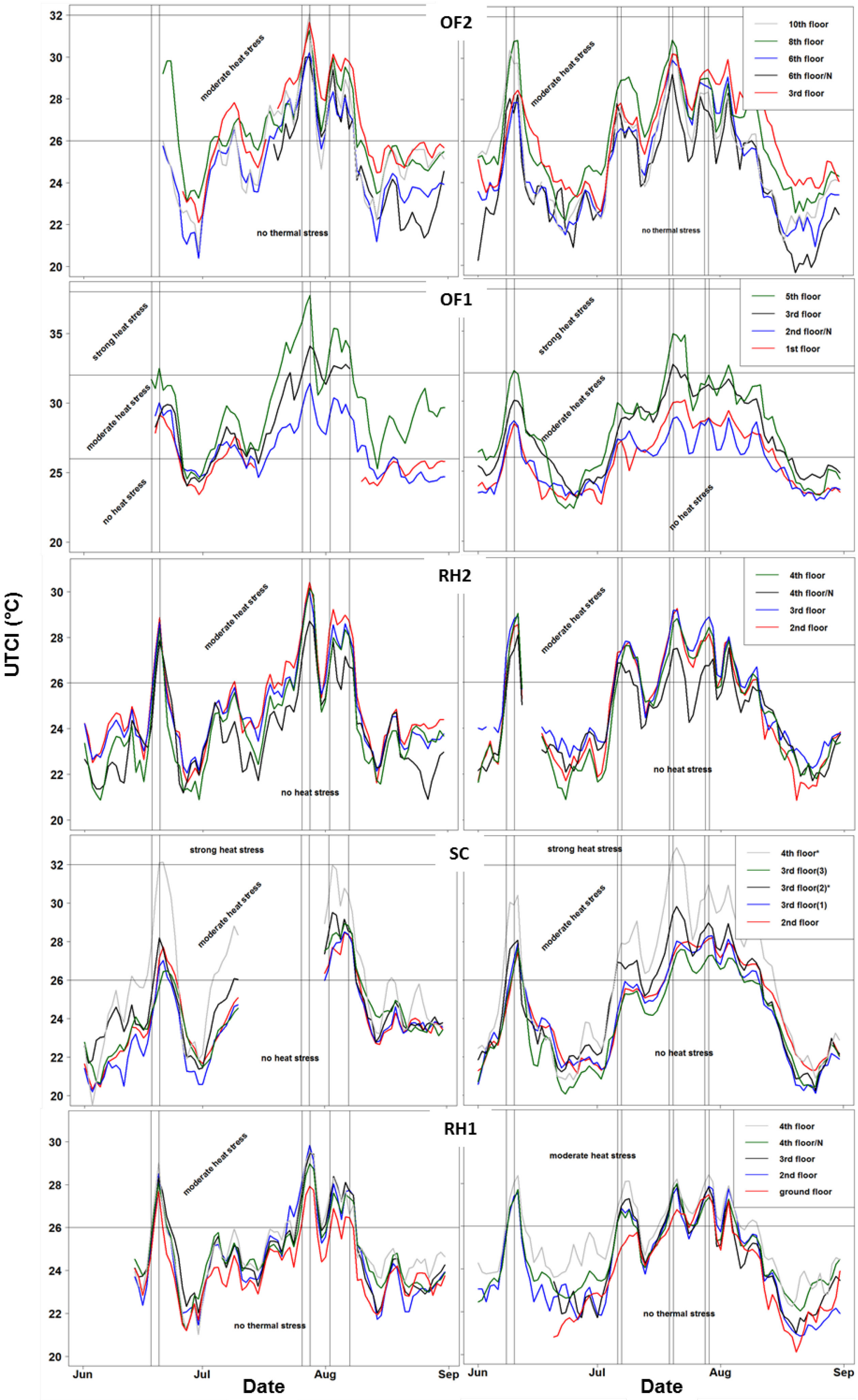
The highest indoor heat stress levels were calculated at OF1. For two days in 2013, the maximum UTCI values on the 5th floor exceeded the 38 °C threshold for very strong heat stress. On average, OF1 shows increasing heat stress levels with increasing floor level. RH1 showed the same pattern within the building but lower UTCI values (31.6 °C max). The thermal load at the RH2 was similar to RH1. However, the distribution within the building was the opposite, with decreasing UTCI with increasing floor level, as also observed at OF2, where the lowest floor (3^{rd}) has the highest mean heat stress levels. The UTCI distributions at the school differed from the other sites. In addition to the rooms in the old building (SC), two rooms are located in the 2006 enlarged top floor (SC*) with different window sizes and wall constructions. The mean UTCI in SC* (25.0 °C) exceeded the value in SC (23.8 °C). The internal mean UTCI variation between the rooms at the school and at the two residential care homes for the elderly varied by approximately 1 K. The two office buildings in contrast showed noticeable differences of 4-7 K among the rooms. A time delay, the so-called lag effect after the beginning and the end of the heat waves, can be observed in all buildings, but it is unequally distributed.

Fig. 3.4 shows the UTCI distribution at the study sites during the different warning levels in 2013 and 2014. On average, UTCI values increased with increasing warning classes. Due to the big sample sizes, the UTCI threshold of 26 °C and even the 32 °C one are exceeded at some points during warning class 0. At three study sites, the upper quartile was above the 26 °C threshold of moderate heat stress. Furthermore, extreme values at four study sites exceeded the strong heat stress limit and at OF1 the 38 °C threshold when no heat stress warning was issued (class 0). The differences in sample size were mainly due to the varying number of rooms per study site (Table 3.1) and some data gaps.

Fig. 3.5 displays hourly indoor UTCI mean values for all days during the seven HWs divided into day (11am-7pm) and night (8pm-10am). Almost every day, the heat load exceeded the 26 °C UTCI threshold for moderate heat stress at both times of the day. During the day at OF1, UTCI values exceed the 32 °C limit (strong heat stress) during the 2^{nd}, 3^{rd} and 6^{th} HWs. Despite the lower average UTCI values at night, the difference between day and night was low (mean= 0.6, min= -0.3, max= 2.7) and therefore the potential to recover from thermal stress is reduced. On some days, especially during HW4, the mean thermal load at night was even higher compared to the day.

(next page)

Figure 3.3 Mean daily indoor UTCI values presenting the spatial/temporal heat stress variability in all rooms at all study sites; left=2013 and right=2014; horizontal lines indicate 26 °C and 32 °C UTCI thresholds for moderate and strong heat stress levels; vertical lines show the beginning and end of each heat wave; due to readability only five of the seven rooms at study site SC are displayed, the first excluded is similar to the 3^{rd} floor (2) in the new portion and the second one to the 2^{nd} floor in the old portion



OF2
OF1
RH2
SC
RH1
10th floor
8th floor
6th floor
6th floor/N
3rd floor
5th floor
3rd floor
2nd floor/N
1st floor
4th floor
4th floor/N
3rd floor
2nd floor
4th floor*
3rd floor(3)
3rd floor(2)*
3rd floor(1)
2nd floor
4th floor
4th floor/N
3rd floor
2nd floor
ground floor
strong heat stress
moderate heat stress
no heat stress
no thermal stress
UTCI (°C)
Date
Jun
Jul
Aug
Sep

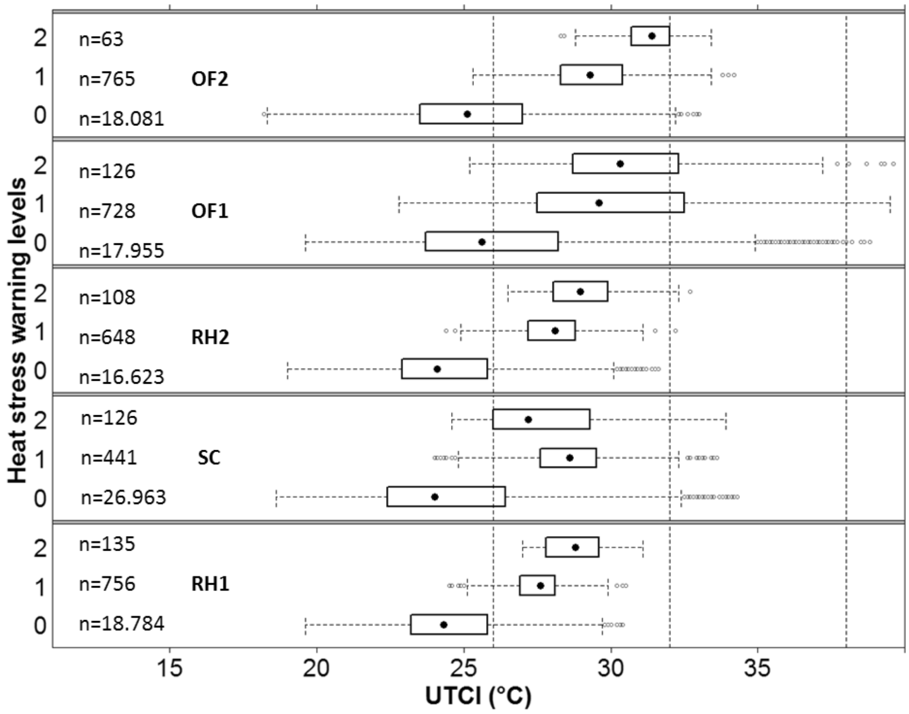


Figure 3.4 Hourly indoor UTCI values (°C) at different warning levels at all study sites during summer 2013 and 2014; warning levels: 0=no warning, 1=strong heat load, 2=extreme heat load; n=sample size; vertical lines indicate UTCI heat stress thresholds (26 °C moderate heat stress, 32 °C strong heat stress, 38 °C very strong heat stress)

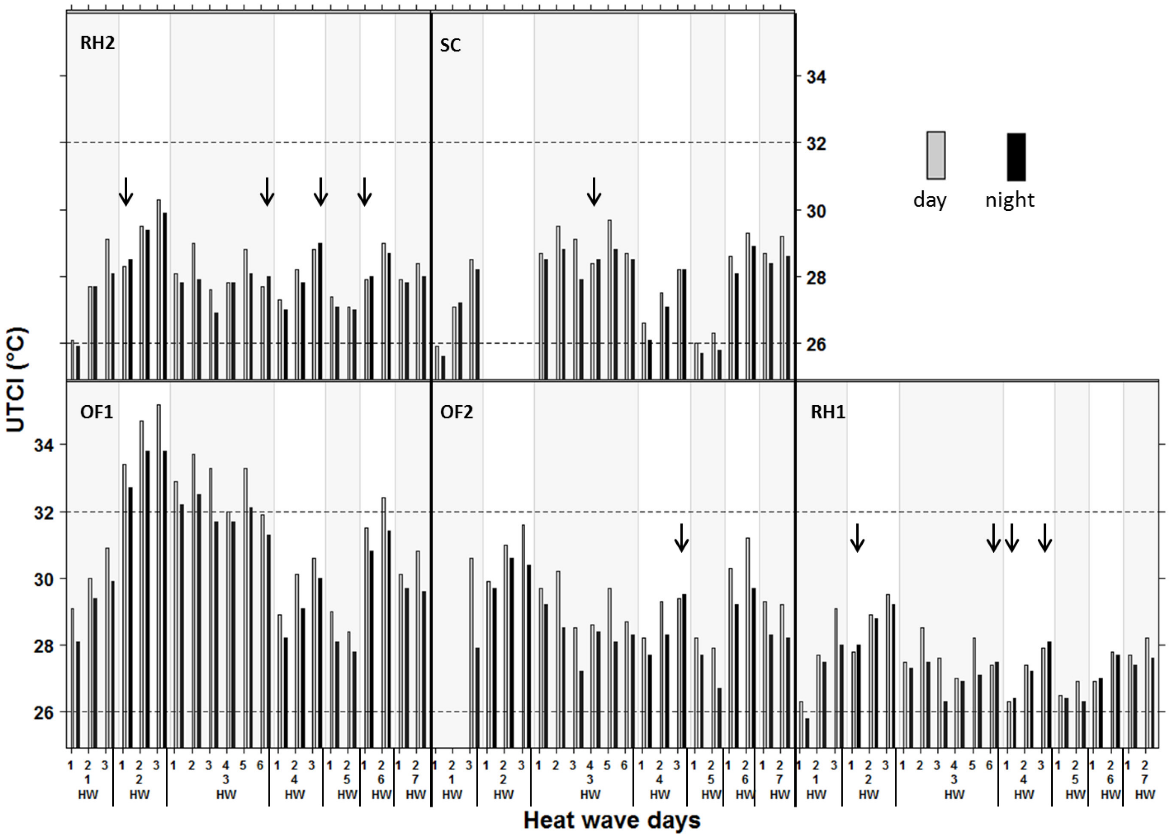


Figure 3.5 Mean hourly indoor UTCI values (°C) during the seven heat waves (1-7HW) in 2013 and 2014 divided into day (11am-7pm) and night (8pm-10am) at all study sites; horizontal lines indicate the 26 °C and 32 °C UTCI threshold lines for moderate and strong heat stress; vertical lines show the start and end of the heat waves; arrows indicate days with a higher heat load at night than that during the day

3.3.2 Driving factors of the spatial and temporal variability of indoor heat stress

3.3.2.1 Outdoor climate

Previous studies show that outdoor climate is the main driving factor regarding indoor climate. This result is confirmed by the results of this study. The analysis of indoor and outdoor UTCI during summer 2013 and 2014 resulted in an r^2 value of 0.6 ($p<0.01$), indicating that 60% of the variance of indoor UTCI can be explained by outdoor UTCI. The individual examination of each study site showed correlation coefficients between 0.76 and 0.88 and therefore strong correlations between indoor and outdoor UTCI with small differences between the study sites. To examine if on-site measurements are a better indicator for indoor climate, we repeated the study with data from a central weather station. Table 3.4 summarizes the correlation results ($p<0.01$) between indoor UTCI/Ta and outdoor UTCI/Ta based on data from the on-site measurements and on data from the central weather station. The highest correlation was found between indoor Ta and outdoor Ta.

Table 3.4 Correlation coefficients between indoor UTCI (Ta) and outdoor UTCI (Ta) based on facade/station measurements

	UTCI-UTCI		**Ta-Ta**	
	indoor-facade	indoor-station	indoor-facade	indoor-station
SC	0.76	0.83	0.82	0.84
RH1	0.86	0.89	0.87	0.88
RH2	0.83	0.90	0.91	0.92
HO	0.88	0.88	0.93	0.93
H1	0.76	0.85	0.83	0.84
H2	0.79	0.82	0.84	0.84

For comparing indoor UTCI with outdoor UTCI at different times of the day, we used the warning period 11am-7pm for daytime and 8pm- 10am for nighttime when no warnings are issued. Fig. 3.6 and Fig. 3.7 display the results for daytime and nighttime, respectively. During the day outdoor UTCI exceeds indoor UTCI of approximately 5.6 ± 3.9 K (max 15.1 K; min -2.5 K). The second day of the 5th heat wave was the only day when mean indoor UTCI was higher than that outdoors at all study sites during the daytime. During night, the typical situation is the opposite. Indoor UTCI exceeds outdoor UTCI of approximately 3.8 ± 2.1 K (max 8.4 K; min -1.9 K).

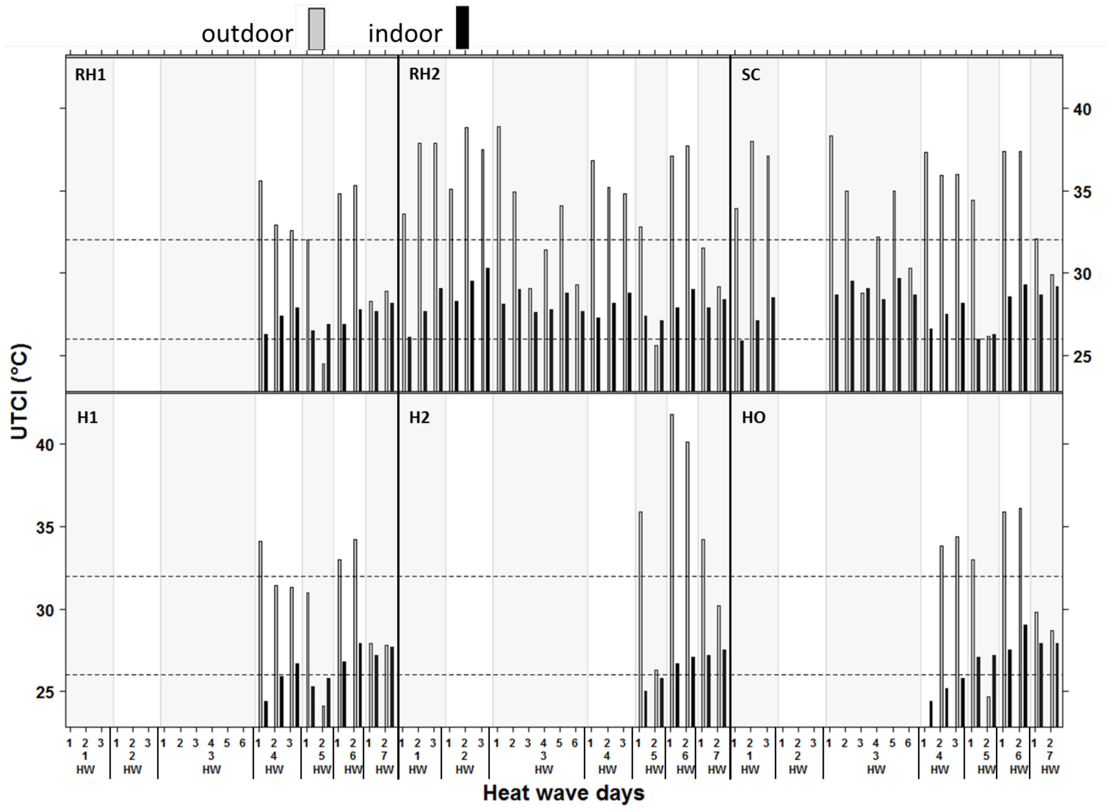


Figure 3.6 Mean hourly indoor (black) and outdoor (grey) UTCI values (°C) during the seven heat waves (1-7HW) in 2013 and 2014 at ***daytime*** (11am-7pm) at all study sites; horizontal lines indicate the 26 °C and 32 °C UTCI threshold lines for moderate and strong heat stress; vertical lines show the start and end of the heat waves

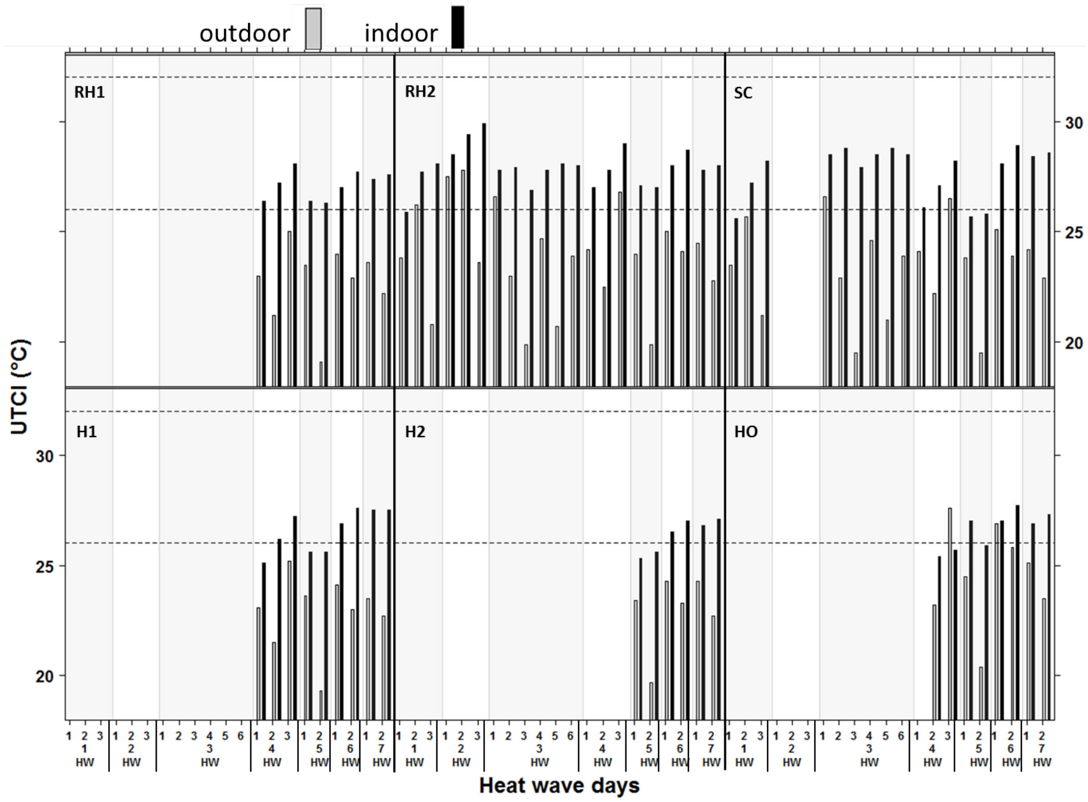


Figure 3.7 Mean hourly indoor (black) and outdoor (grey) UTCI values (°C) during the seven heat waves (1-7HW) in 2013 and 2014 at ***night*** (8pm-10am) at all study sites; horizontal lines indicate the 26 °C and 32 °C UTCI threshold lines for moderate and strong heat stress; vertical lines show the start and end of the heat waves

3.3.2.2 Building characteristics

The description of the variability of heat stress in the first part of the results indicates that some building characteristics may influence the UTCI. The first physical parameter we analyzed was floor level to determine if the observable differences are significant. The correlation between floor levels and UTCI over all measurement sites showed a very weak but positive relationship (r= 0.21, p= 0.01). However, it is likely that the influence of floor level on one side is overlain by a small effect of another building. Hence, the sites have been analyzed separately. Five of the six sites showed a very weak or no correlation (p= 0.01) between floor level and UTCI (RH1 r= 0.22, SC r= 0.0, SC* r= 0.16, OF2 r= -0.09, RH2 r= -0.08). The negative correlations at OF2 and RH2 can be seen in Fig. 3.3, where on average the highest UTCI values occurred at the lowest floor levels. OF1, in contrast, showed a positive correlation (r=0.64; p=0.01). Other building characteristics used in this study were year of construction and size of the window surfaces in each building (Fig. 3.8). The size of the window areas showed a very weak relationship with the UTCI (r= 0.18; p= 0.01), as well as the year of construction with the UTCI (r= 0.13, p= 0.01). We found no differences when repeating the analysis using only daytime or nighttime UTCI values.

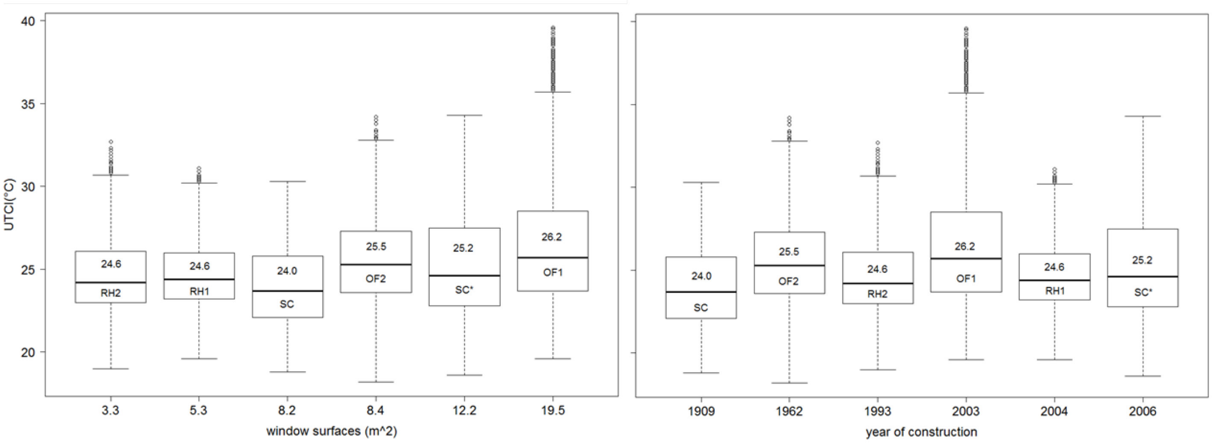


Figure 3.8 Analysis of the influence of the building characteristics 'size of windows' (m^2) (left panel) and 'year of construction' (right panel) on the UTCI (mean hourly values)

3.4. Discussion

3.4.1 Indoor heat stress during warning periods

The analysis shows that indoor heat stress during summer 2013 and 2014 was unequally distributed regarding spatial and temporal variability, especially over the course of the heat waves. The examination of indoor UTCI during the warning periods showed heat stress (>26 °C) at all warning levels (Fig. 3.4), indicating the importance of this analysis. Specifically, the high values at warning level 0, when no warning is issued, are noticeable. It is likely that the high UTCI values during class 0 can be traced back to the time limitation of the warning period from 11am to 7pm. In indoor environments the thermal load lasts longer compared to outdoors due to the absorption of solar radiation during the day and the disposal of thermal radiation during the night. Therefore, UTCI values after 7pm were still high but are not included in the warning classes. These results are confirmed by the comparison of the day and night indoor UTCI values (Fig. 3.5). The differences were small and on some days the night showed higher values than the previous day. The comparison of outdoor UTCI with indoor UTCI supports this finding. The diurnal course of indoor UTCI was dampened due to the heat transfer resistance of the walls and their heat capacity. This lead to an additional thermal load during night when the strain outdoors was mostly reduced (Fig.3.7). In summary, people within the study rooms are affected by heat stress not only during day but also during night. Hence, the ability to cope with heat stress after a disturbed recovery phase at night is likely to decrease due to a possible accumulation effect of heat stress (Parson 2003). Based on these results it is recommended to adapt the heat warnings to indoor environments and to expand the warning periods to 24h warnings. Especially during the recovery phase at night, it is important to recommend adequate adaptation strategies to reduce the heat stress risks.

When using the official heat warnings of the DWD, some limitations have to be considered. The warnings are based on the thermal index *'Gefühlte Temperatur'* (index of the DWD) and not on the UTCI. Hence, the warning levels/thresholds are not fully concordant. We used the UTCI to provide results, which are comparable to other studies and can easily be reproduced. The aim of this part of the study is to show the thermal load during official warnings and not to revise the warning system itself. Hence, the differences between warning levels due to the use of different indices are negligible for the conclusions of this study. Furthermore, the detailed study by Blazejczyk et al. (2012) showed that indices using complex thermal exchange models (e.g. UTCI, *'Gefühlte Temperatur'*) are highly correlated.

3.4.2 Driving factors of indoor heat stress

3.4.2.1 Outdoor climate

The second part of the study was executed to identify the main driving factors for the differences in indoor heat stress. The fact that indoor climate is mainly governed by outdoor climate (Höppe 1993, Franck et al. 2013, Nguyen et al. 2014, Quinn et al. 2014) is confirmed by the results of this study. However, our second assumption that on-site measurements provide a better explanation for indoor climate cannot be confirmed. The correlation between indoor climate and the central weather station was higher, independent of the variables UTCI or Ta (Tab. 3.4). One possible explanation is the position of the facade station. The sensors were mounted on different floors as close to the indoor measurements as monumental protection and mounting options allowed. Ta showed on average higher values and bigger daily amplitudes compared to the standard reference weather station due to the additional influence of the thermal radiation of the building. Furthermore, we found a higher relationship between outdoor Ta and indoor UTCI. Outdoor RH and v are therefore not decisive regarding the development of indoor climate. This finding is confirmed by the highest correlation between indoor and outdoor Ta.

3.4.2.2 Building characteristics

The correlation between indoor UTCI and different building characteristics (Tab. 3.1) was very low suggesting that floor level, size of the window and year of construction are not good indicators for UTCI in indoor environments. However, at some study sites, indoor heat stress can be specified through the combination of more than one building characteristic. At OF1 where the highest heat stress levels were measured, floor level correlates with UTCI (r=0.64) and the building has the largest window surfaces. This may suggest that for modern buildings with large window areas and thus a big impact of direct sunlight on indoor climate, the position of a room within a building is an important consideration or at least the size of the windows. The influence of multiple variables can be further seen in the comparison of OF1 with RH1. OF1, constructed in 2003 with big window areas, experienced the highest heat stress levels whereas RH1, constructed in 2004 with relatively small window areas showed one of the lowest UTCI values in all buildings. The correlation of UTCI with all window sizes was very low. Nevertheless, a tendency to have higher UTCI values in rooms with a bigger window surface is observable. The two office buildings, as well as SC*, had the highest maximum heat stress levels and concurrently the largest window surfaces (Fig. 3.8).

The study site SC is of a special interest due to two different window surfaces and two different years of construction combined in one building (Tab. 3.1). Built in 1909, SC consists of thick solid stone walls. This type of wall has a lower heat transmission coefficient (~1.2 W/m^2K) compared to glass (2.8-5.9 W/m^2K) (Schulze 2004), and the rooms within this part of the building need more time to heat up and cool down, which can be seen in the pronounced lag effect and on average lower heat stress levels (Fig. 3.3). Rooms within the new part (SC*) are of a lightweight construction and hence heat up more quickly. The UTCI values had higher pronounced daily cycles and higher peaks. Furthermore, the average UTCI values within SC (window size of 8.2 m^2) were lower compared to the new part (12.2 m^2). In contrast, RH1 with a window area of 5.3 m^2 experienced higher heat stress levels than SC (8.2 m^2). This deviation can be explained again by the construction of the building. In addition to the thick solid stone walls, the size of the room is bigger than the other study rooms. Hence, the higher amount of solar radiation entering the rooms was dampened due to the lower heat transmission coefficient of the wall and the bigger air capacity. These characteristics lead to a compensation of the bigger window surfaces. Nevertheless, to confirm these results, more study sites of the same types are needed.

3.4.2.3 User behavior

As a last possible driving factor of indoor heat stress, it is important to consider user behavior. We did not consider it within our study, but the results already indicate a possible influence. RH2 shows a reversed UTCI distribution with the highest values at the lowest floor and vice versa. This was very likely due to the behavior of the people within the rooms, i.e. room ventilation, shading of the room. At the highest floor, the person was aware of heat stress risks and took measures to reduce it, whereas the person at the lowest floor was bedridden. A further example is at OF2, where the lowest floor experienced the highest UTCI values. The room was the only one not in use. The influence of user behavior can also be found in the lag-effect at the study site SC. During the first heat wave, summer holidays started and no measures to reduce the heat stress could be taken. After the third event, the lag-effect is less pronounced due to influencing user behavior during school days. In summary, the consideration of user behavior is important, and studies regarding indoor heat stress should include this factor.

3.4.3 UTCI corrections

Using the UTCI in indoor environments requires some explanations. The UTCI was developed and evaluated for outdoor conditions and hence, is not applicable indoors. However, when describing indoor heat stress, it is important to consider the outdoor conditions. Furthermore, we built our study on all relevant meteorological parameters influencing human bioclimate and not just on Ta. It is therefore necessary to use a rational index with a thermal comfort model and further to consider the human physiology (Fiala et al. 2012), as well as the influence of clothes (Havenith et al. 2012).

Currently, the use of the UTCI in indoor environments has some limitations pertinent to this study. First, v is not within the range of validation for the UTCI calculation (see 2). This increase in v possibly leads to an underestimation of heat stress because within the UTCI calculation higher v levels reduce the thermal load. Second, the activity of a person is above the average indoor levels, where a sitting position (55 W/m^2) is the main activity. The determination leads likely to an overestimation of heat stress due to a higher internal heat production and hence a higher thermo-physiological model output. A first attempt to overcome some limitations regarding different activity levels and exposure times had been conducted by Bröde et al. (Leibnitz Institut; not published) for outdoor conditions. Based on their results, we used their UTCI correction terms considering activity at a resting level with a metabolic rate of heat production of 1.1 met (1 met = 58.15 W/m^2) and exposure duration covering an 8-hour shift length in 30-min steps because they are similar to indoor conditions. The results are presented in Fig. 3.9 and show lower UTCI values on average at all sites. However, the results do not include a modification regarding v. Due to the incompleteness and missing evaluation of this UTCI adaptation for indoor environments, we do not consider the correction terms in the analysis but emphasize the need for further study regarding this area.

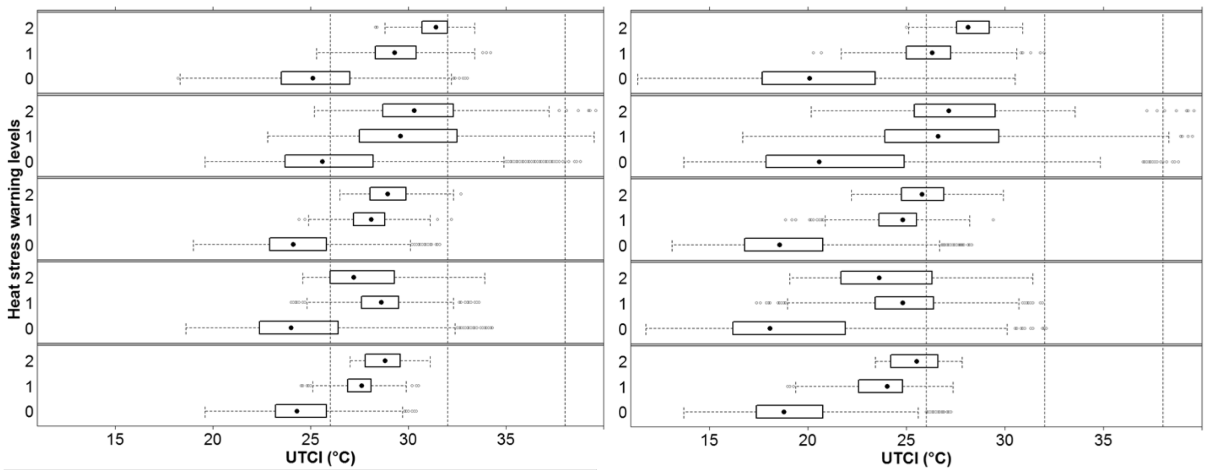


Figure 3.9 Indoor UTCI values at different warning levels at all study sites. 0=no heat load, 1=strong heat load, 2=extreme heat load; left=standard UTCI; right= UTCI with correction terms

3.5. Conclusion

Heat stress occurred on 34 % of all days in summer 2013 and 2014 either during day or at night in Berlin. Indoor heat stress in mid-latitude cities is therefore a major hazard and may be amplified in the next decades due to the global increase in Ta. More effort in understanding the causes and creating effective countermeasures to reduce indoor heat stress is needed. The spatial variability within the city needs to be considered too, especially regarding local adaptation strategies. During heat waves, indoor heat stress at night is higher than that outdoors due to the thermal inertness of the buildings. As a consequence the recovery phase during night is disturbed, and it is likely that the ability to cope with heat stress during the next day will be decreased. Hence, the warning period of the official service during daytime is not enough for indoor environments. We recommend extending the warning periods and adapting the warning system to indoor environments.

Regarding the development of indoor heat stress, the study confirms that indoor climate is mainly governed by outdoor climate. Furthermore, we found that on-site measurements of outdoor climate provide no better explanation of UTCI variability indoors, and therefore central weather station data can be applied for the assessment of indoor conditions. For a more detailed analysis of the interactions between indoor and outdoor climate, a building model has to be applied. The analyzed building characteristics are not good indicators for UTCI. However, we found some relationships between the sizes of the window areas and maximum UTCI values. We assume that real-case experimental studies complicate the analysis of influencing building characteristics, indicated also by the possible influence of user behavior. Moreover, more study sites of the same type should be used. For future studies, we also recommend to monitor user behavior during the measurements like opening and closing of windows to control ventilation or shading of windows to control radiation.

Acknowledgements

We would like to thank the German research foundation (DFG) for funding Research Unit 1736 'Urban Climate and Heat stress in mid-latitude cities in view of climate change (UCaHS)' (EN138/21-1, SCHE 750/8-1 and SCHE 750/9-1) and Phillip Schuster for his support with data collection.

CHAPTER 4: ANALYSIS OF OUTDOOR AIR TEMPERATURE AS AN ADEQUATE MEASURE TO ASSESS INDOOR HEAT EXPOSURE

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Submitted to:

Indoor Air

Abstract

Many studies have focused on outdoor environments regarding the implications of heat stress on health, whereas modern society spends most of their day indoors. We analyzed the relationship between outdoor temperature and indoor temperature using data from an indoor measurement system and outdoor weather stations from 05/01/2013 until 04/30/2015. The results showed a consistent relationship with a strong correlation between outdoor and indoor temperatures. We further observed a segmented relationship, following a hockey stick form. The relationship changed at a daily mean temperature of 12 °C, a daily maximum temperature of 18 °C and a daily minimum temperature of 9 °C. In particular, above a threshold temperature, we found a strong and consistent correlation (r=0.82-0.87) for all temperatures. Maximum daytime temperatures in indoor environments remained below outdoor temperatures during heat periods, while nighttime indoor temperatures were consistently higher. We observed no evidence of a time lag between outdoor and indoor temperatures, using a distributed lag non-linear model. Using the observed relationship between outdoor and indoor temperatures, we calculated indoor temperatures for the time period from 01/01/2000 to 12/31/2010. Both predictors revealed similarly strong effects on mortality while showing no differences with regard to shape, slopes or predictive power.

Key words: Indoor heat exposure, Mortality, Two-year measurement, Temperature, Indoor, Outdoor

Practical Implications

This study analyses whether outdoor air temperature is an adequate measure to assess indoor heat. The results indicate that there is a strong relationship between indoor and outdoor air temperature. Furthermore, the study underlines the importance of indoor climate regarding heat stress, especially during the night, but also suggests the adequacy of using outdoor temperatures as heat indicators given the strong and consistent association.

4.1 Introduction

Climate change is not only responsible for increasing temperatures in general but also for the increase in frequency and intensity of extreme events such as heat waves (Schär & Jendritzky 2004, IPCC 2013b). The accompanied risk to human health has been well investigated and the link between elevated temperatures and mortality rates is widely accepted in the scientific community (Basu & Samet 2002, Medina-Ramón & Schwartz 2007, Basu 2009, Michelozzi et al. 2009b, Almeida et al. 2013). In this context, urban agglomerations are of particular interest because adverse heat effects are likely to increase due to additional higher temperatures caused by the UHI (urban heat island) effect (Matzarakis & Endler 2010).

So far, most studies used outdoor temperatures as a predictor of health outcomes, as such data is widely available over large time periods at a high temporal resolution. In modern society, the majority of time (90 % per day) is spent indoors, and consequently, individuals are mostly exposed to an indoor climate (Höppe 1993). Especially during night, when adaptation measures, such as changing locations, are limited, increased temperatures can affect sleep quality and hence well-being and health (Libert et al. 1991, Bach et al. 1994, Okamoto-Mizuno & Tsuzuki 2010). Studies by Laaidi et al. (2012) and Oudin Åström et al. (2011) even indicated a possible increase in mortality due to elevated night temperatures.

During the last few years, the consideration of indoor climate regarding human health increased, as indicated by several studies (Wright et al. 2005, White-Newsome et al. 2012, Franck et al. 2013, Uejio et al. 2016). The results of these studies are consistent in showing higher thermal loads indoors and hence a higher risk for negative health implications due to indoor heat exposure during extreme events. All these studies are based on indoor climate measurements and are therefore very costly, time-consuming and due to their limited timespan, cannot be used for the long-term assessment of health effects. Studies in which the indoor climate is not the key aspect, e.g., epidemiological or ecological studies, need easier measures to assess indoor climate. Quinn et al. (2014) tried to overcome this limitation by modeling the relationship between indoor and outdoor conditions based on temperature and humidity measurements. Their results indicated that indoor heat is strongly associated with outdoor conditions and varies considerably between sites. However, their study focused on extreme events and the analysis was based on indoor measurements which were limited to a couple of days per measurement. Smargiassi et al. (2008) used a GIS-based regression mapping approach to model urban spatial indoor temperature patterns based on measured indoor and outdoor temperatures. Their indoor temperature prediction model indicated that indoor temperatures are likely to represent the exposure to indoor heat more accurately. However, their model is limited to urban areas and needs several input variables such as surface temperatures and building characteristics which may not always be available. Furthermore, none of these studies focuses on the difference in indoor heat exposure during the day and night.

Our study aims to estimate whether outdoor temperature is an adequate measure to assess indoor heat exposure during the day and night. Outdoor data are usually easily accessible, intensely measured and usually standardized. In this study we used indoor data acquired during a 2-year measurement campaign (Walikewitz et al. 2015a) and outdoor data from central weather stations distributed over Berlin, Germany. Our study consists of three steps: We initially (1) analyzed the association between outdoor air temperature ($Ta_{\_outdoor}$) and indoor air temperature ($Ta_{\_indoor}$) over the 2-year measurement period from 05/01/2013 until 04/30/2015 and derived parametric relationships. Furthermore, we used distributed lag non-linear models (dlnm) to look for time displacements between outdoor and indoor temperatures. Then (2), this association was used to calculate $Ta_{\_indoor}$ based on outdoor data for an extended period of ten years from 2000 until 2010. Finally (3), we fit generalized additive models (GAM) adjusting for various confounding variables in order to assess the predictive power of outdoor vs indoor temperatures on indoor heat exposure and hence on mortality.

4.2 Materials and Methods

4.2.1 Data

The study was based on outdoor and indoor climate data as well as mortality. **Indoor** air temperature data were obtained through a detailed measurement system run between 05/01/2013 and 04/30/2015 in eight different buildings distributed over Berlin. Between 2 and 7 rooms per building (31 in total) were equipped with two Testo 174H loggers (accuracy of ±0.5 °C). The sensors were fixed at a height of approximately 1.1 m above the ground. The investigated rooms in each building were located at different floor levels but were equal in size and orientation of the windows (southwest) and were not influenced by air-conditioning. To estimate the average thermal conditions per room, we avoided the placement of sensors at locations where they may have been influenced by direct solar radiation or heating. All data were recorded at 5-minute intervals and then aggregated to mean, minimum and maximum daily values if all data on a given day were available. $Ta_{\_indoor}$ was then calculated for each study site and furthermore calculated by aggregating all eight indoor study sites to one average indoor air temperature value. For a more detailed description of the settings as well as of the study site characteristics, see Walikewitz et al. (2015a). **Outdoor** air temperature data were compiled from daily temperatures for the period from 2000 to 2010 and 2013 to 2015. The arithmetic mean, minimum and maximum temperatures for the three airport stations Tegel, Tempelhof and Schönefeld in Berlin were provided by the German National Weather Service (DWD).

Air pollution data were provided by the Berlin Senate Department for Urban Development and Environment. Three urban background stations (Neukölln, Wedding and Buch) were chosen, and daily averages of Nd, PM_{10} and O_3 were generated from half-hourly measurements. Subsequently, a Berlin-wide daily mean value was determined by averaging all three stations. **Mortality** data were obtained from the research data center of the Federal Statistical Office and the statistical offices of the Länder (Federal state), containing daily patient data documented by all hospitals. The data-set comprised daily death counts for the entire population of Berlin from 2000 to 2010 (274,275). They report all-cause (190,079) as well as cause-specific cases, divided into cardiovascular (58,273; WHO ICD-10 I00-I99) and respiratory failure (25,923; WHO ICD-10 J00-J99).

4.2.2 Statistical methods

For all statistical analyses, model fitting and regression analyses we used the R Version 2.15.1 (RCoreTeam 2012).

Indoor and outdoor air temperature relationship

To get a first impression of the distribution of $Ta_{\_indoor}$ and $Ta_{\_outdoor}$ we obtained descriptive statistics, such as median and percentile calculations. Density plots were further used to examine the distribution of daily mean, minimum and maximum temperatures. A specific focus was given to minimum Ta, which represented the situation at night. Linear and piecewise linear regression was then used to analyze the relationship between $Ta_{\_indoor}$ and $Ta_{\_outdoor}$, in a similar way to the approach suggested by Nguyen et al. (2014). A segmented relationship (using the R package 'segmented') was fitted to identify threshold values where the slope of the relationship changes significantly. We then calculated the correlation coefficient before and after the breakpoint. Due to the thermal inertness of buildings, we were further interested in assessing the lag time between outdoor and indoor temperatures. Therefore, we used a distributed lag non-linear model (dlnm). The model is fitted through a generalized additive model (GAM) with Poisson family and with the following choices regarding the control of confounders: b-splines and indicator variables for month and year. The lag-time was set to 7 days following the results of earlier studies. For further details see Gasparrini (2011). To show the variance across measurement sides, we constructed box plots that compared the variance of breakpoints and slopes of every indoor measurement site to assess differences between study sites and to look for differences between mean, maximum and minimum indoor air temperatures. The results of the linear and piecewise linear regression (i.e., slopes) were then used to calculate the indoor air temperature from 2000 to 2010.

Statistical modeling

The association between indoor/outdoor air temperature and mortality from 2000 to 2010 was analyzed using distributed lag non-linear models (dlnms) and Poisson generalized additive models allowing for linear and non-linear confounding effects. We investigated the short-term mortality displacement using a dlnm, as described in Gasparrini et al. (2010). This modeling framework assesses the nonlinear and delayed effects in time-series data concurrently. The model is fitted through a generalized additive model with Poisson family and with the following choices regarding the control of confounders: b-splines and indicator variables for trend, month, public holiday, weekend and day of the week. Following earlier studies, we used lags of up to 21 days to estimate the overall temperature and potential harvesting effects (Qiao et al. 2015). Based on the results of the dlnm, we fitted the models by integrating predictors of the actual and previous days (3-day lag periods). For model fitting, we used the R package 'mgcv'. Penalized regression splines were used to allow for non-linear confounding effects. The degrees of freedom for temperature curves (df) were carried out as an integral part of the model fitting and no a priori number needed to be set. We investigated the thermal effects on cardiovascular, respiratory failure and all-cause mortality. The model was adjusted for trend, month and day of the week, based on the highest predictive power. To check for seasonality, a trend was implemented through a counter variable from one to the end, counting each day. Trend adjustment was modeled using a penalized spline with a fixed number of df. We preselected 5, 6, 7 and 8 df per year and chose 7 df per year based on the UBRE criterion. All other df for trend adjustment were considered robustness checks. The findings indicate a minor impact of the choice of df and suggest a robust model. After including a spline to account for long-term and seasonal variations, we still found a significant effect of the variable month and consequently included month in the model. The variable day of the week, which showed a significant effect, determines the different days of the week where people died in the hospital. Both variables were included as factors. Additionally, we conducted sensitivity analyses by including air pollution data and relative humidity into the models. The outcomes remained mostly unaffected when including either humidity or O3 and PM10 into the models, indicating the robustness of the models. After incorporation of the confounding variables, plots of partial autocorrelation showed no autocorrelation for mortality.

The model was also used for a detailed examination of the relative risk at chosen percentiles (95^{th}, 99.9^{th}) to compare the relative risk of deaths in indoor and outdoor environments.

4.3 Results

4.3.1 Relationship between $Ta_{\_indoor}$ and $Ta_{\_outdoor}$ (2013-2015)

Table 4.1 provides summary statistics of the daily average $Ta_{\_indoor}$ and $Ta_{\_outdoor}$ over the measurement period from 05/01/2013 until 04/30/2015. The indoor and outdoor temperature time series are strongly correlated (r=0.84) and show seasonal patterns with temperature peaks during the summer and troughs during the winter; the amplitude in temperatures is clearly more pronounced for outdoor temperatures compared to indoor temperatures (Fig 4.1).

Table 4.1 Descriptive statistics of daily average indoor and outdoor air temperature in Berlin, Germany, from May 2013 to April 2015

	Indoor	**Outdoor**
Mean (s.d.)	22.49 (2.3)	10.86 (7.2)
Min	18.34	-11.87
25 %	20.88	5.24
Median	21.87	10.12
75 %	23.49	16.33
Max	31.11	28.30

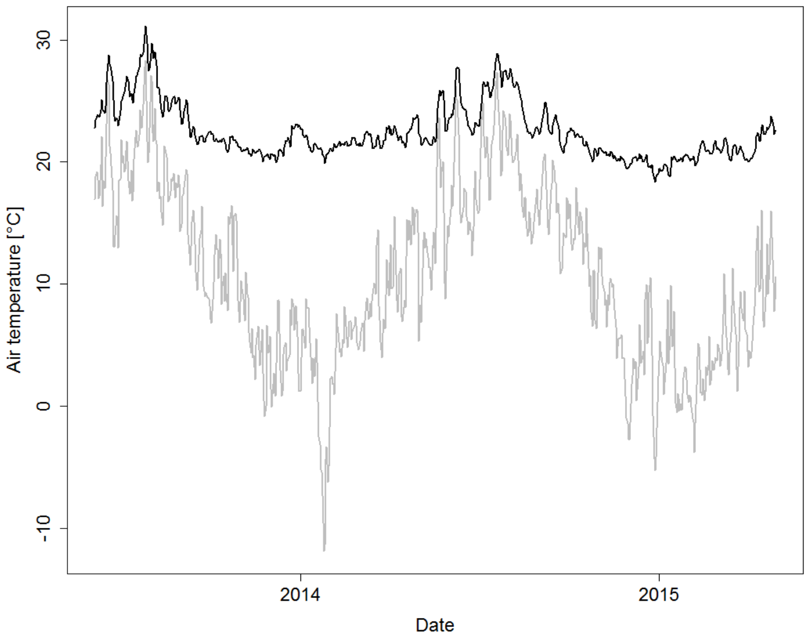

Figure 4.1 Distribution of daily average indoor (black) and outdoor (grey) air temperature in Berlin, Germany, from May 2013 to April 2015

Indoor mean temperatures generally surpass outdoor mean temperatures, even during the summer. Figure 4.2 displays the density distributions for minimum, maximum and mean temperatures. The indoor minimum Ta, representing the nighttime, exceeds outdoor values considerably at the highest temperatures, in contrast to the indoor maximum Ta, which are lower compared to outdoor values (Fig 4.2).

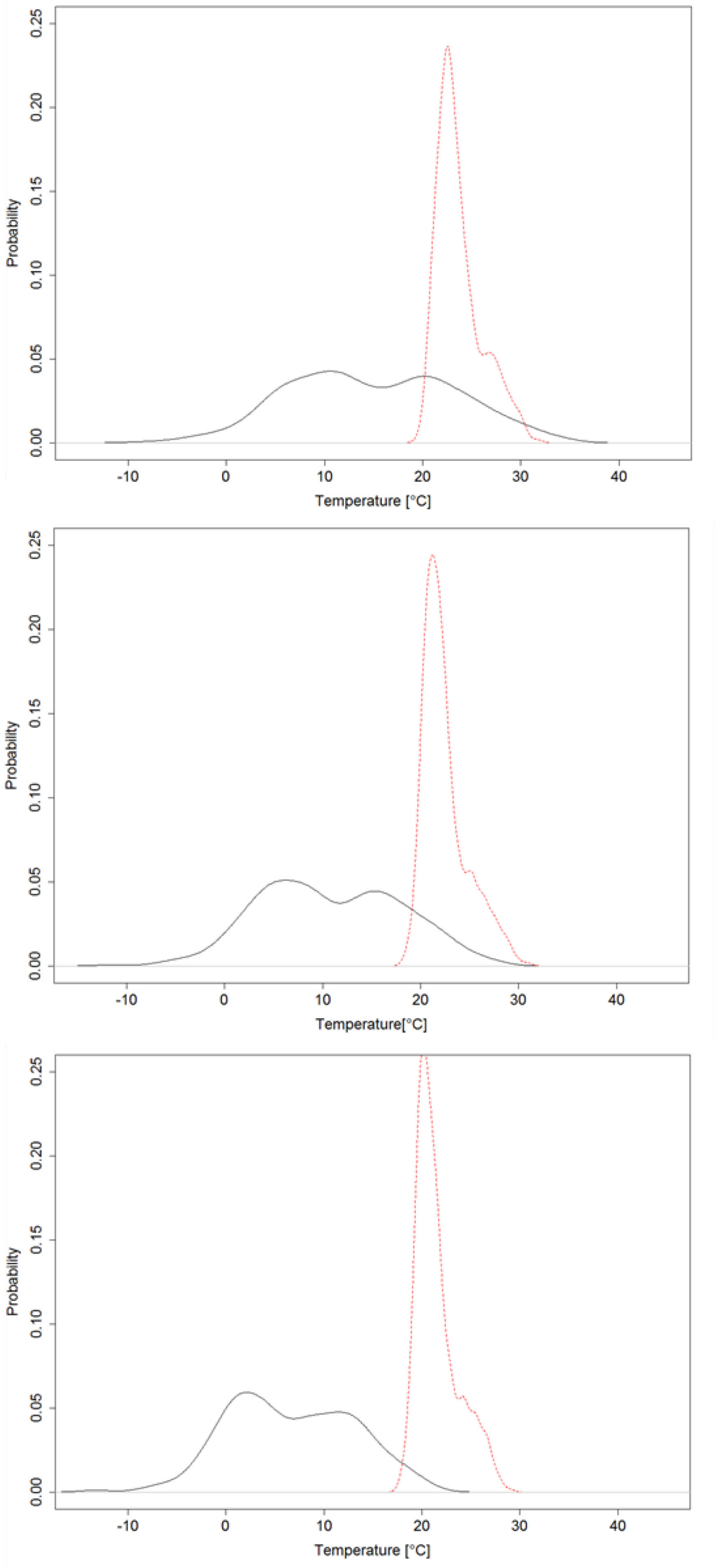

Figure 4.2 Density function of maximum (top), mean (middle) and minimum (bottom) indoor (red) and outdoor (black) air temperature

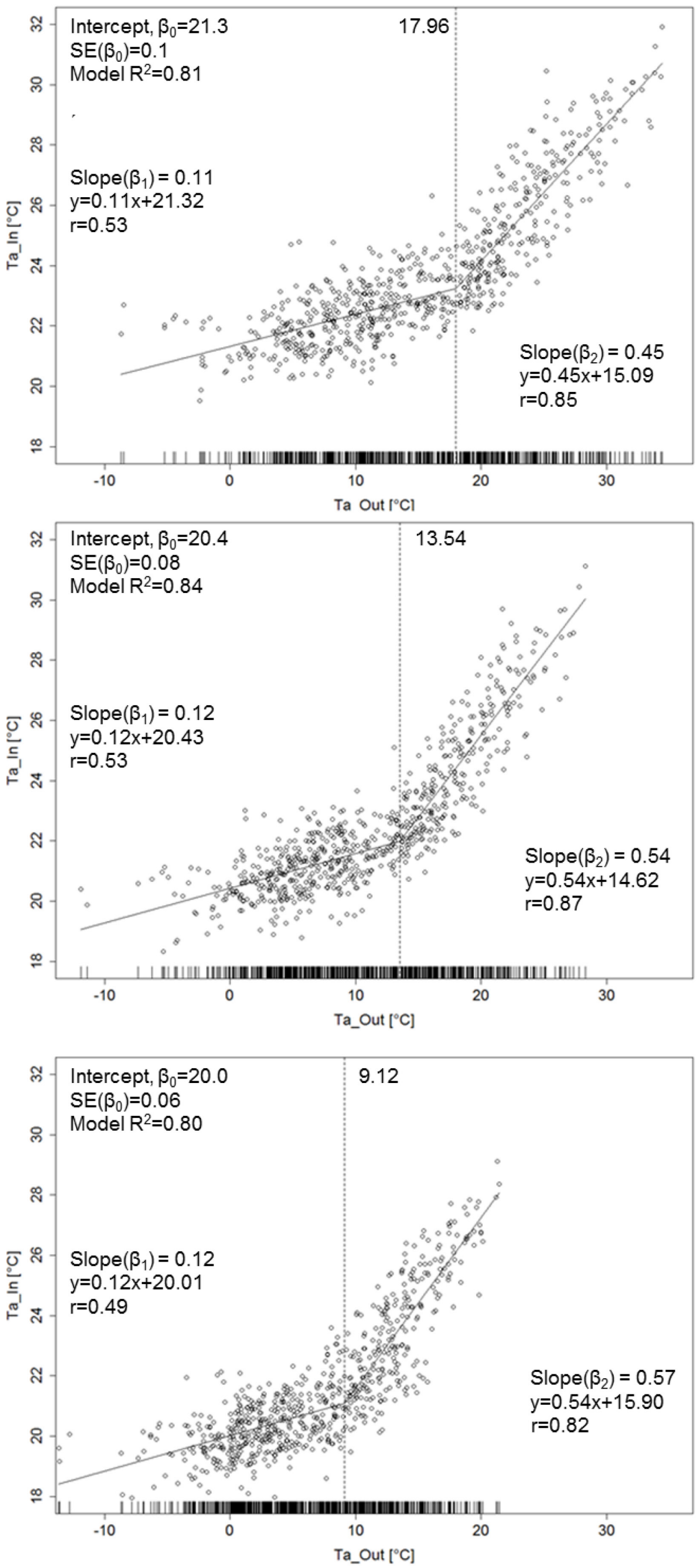

Figure 4.3 Regression results of maximum (top), mean (middle) and minimum (bottom) air temperature relating indoor to outdoor air temperature from June 2013 to Mai 2015; dashed line represents the break point; indoor air temperature is based on the average of all indoor measurements

A piecewise linear regression identified a break point at 13.5 °C for the mean Ta and a strong linear relationship above (r=0.87) and below (r=0.53) this threshold (Fig 4.3). Below the threshold, the slope is smaller (β1=0.12, 95 % CI: 0.10, 0.14) than the linear relationship above the threshold (β2 = 0.54, 95 % CI: 0.51, 0.58). The minimum and maximum Ta were used to conduct an analyses regarding temperature extremes. Thresholds shifted to 9.1 °C for the minimum to 18.0 °C for the maximum Ta with lower correlations below the thresholds (min r= 0.49, max r=0.53) compared to those above the thresholds (min r=0.82, max=0.85). To check for differences between different study sites, we conducted the same analysis for each individual indoor measurement site and used boxplots in order to show the spread (Fig 4.4).

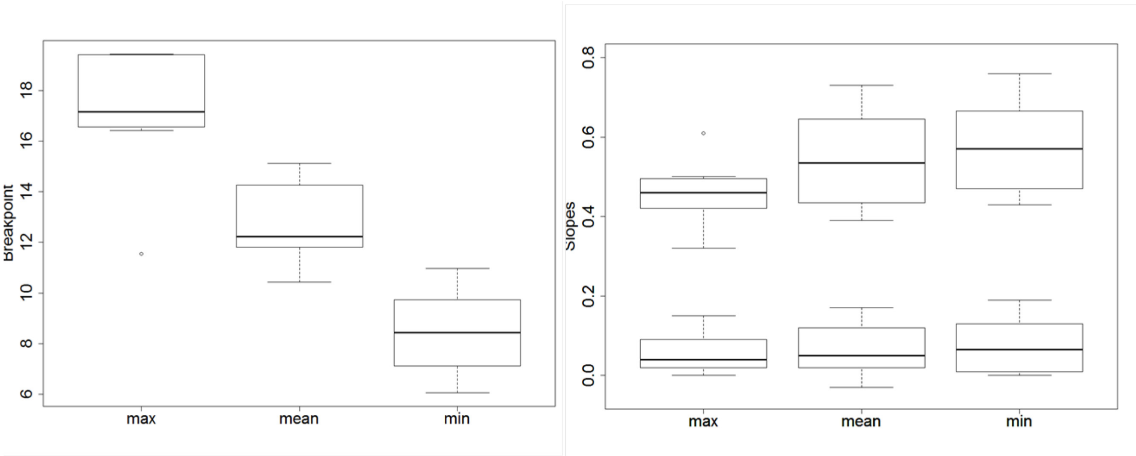

Figure 4.4 Variance of breakpoints (left) and slopes (right) based on the regression results of maximum, mean and minimum indoor and outdoor air temperature of all eight indoor measurement sides

Our analysis further indicated no significant time lag between indoor and outdoor temperatures (Fig 4.5). Based on the average relationship between indoor and outdoor temperatures found between 05/01/2013 and 04/30/2015, we determined $Ta_{\_indoor}$ for the period from 2000 to 2010 based on $Ta_{\_outdoor}$ measured at central weather stations in Berlin. Indoor temperatures were determined for mean, maximum and minimum values.

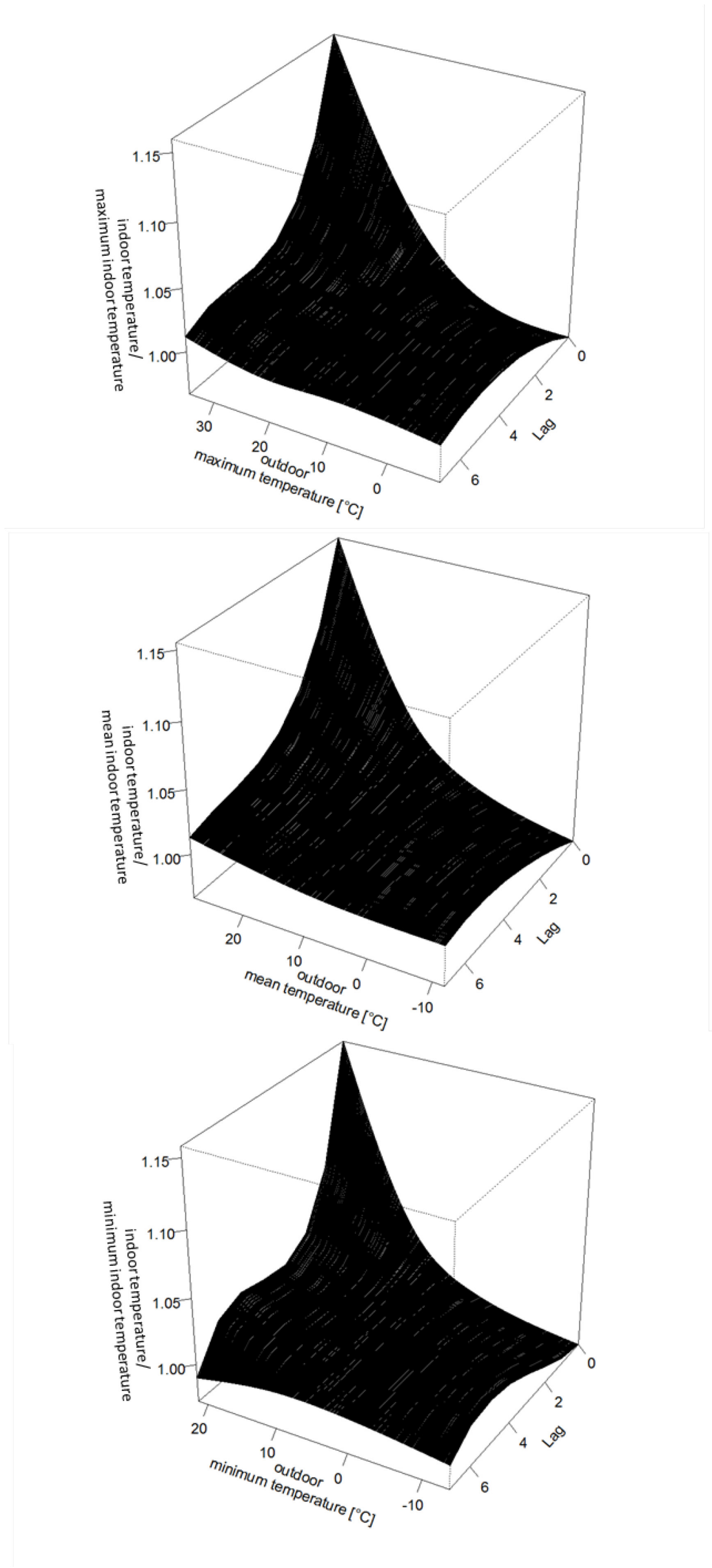

Figure 4.5 Response surface models for different lags regarding the relationship between indoor and outdoor maximum (top), mean (middle) and minimum (bottom) temperatures

4.3.2 Comparison of heat effects on mortality using indoor and outdoor temperatures as predictors (2000-2010)

The response surface models for different lags and outdoor/indoor temperature on mortality data show a very strong and immediate effect of heat (Fig 4.6). Conducting a detailed examination of specific lags (0,3) and temperatures (corresponding to the 95th and 99.9th percentiles of the temperature distribution), the results indicate a change of the temperature-mortality relationship along lags at the highest temperatures (Appendix Fig A.1-A.6). Furthermore, we found a harvesting effect, starting at approximately day 5-7, with no differences between indoor and outdoor environments. Moreover, the harvesting effect did not countervail the heat effect of the previous days. Based on the dlnms, we chose a lag period of 3 days for the subsequent regression analysis.

Figures 4.7-4.9 display the results of the regression analysis between temperature and cardiovascular, respiratory and all-cause deaths. Both predictors, i.e., indoor and outdoor temperatures display a J-shaped curve with mortality. Heat effects tend to be more pronounced in indoor environments, but the results are not significant. When comparing mean (Fig 4.7), maximum (Fig 4.8) and minimum Ta response curves (Fig 4.9), we found no differences in the shapes of the curves. However, the analysis indicates a possible difference regarding the relative risk of dying during extreme temperatures, with the highest risk peaks indoors compared to outdoors. Therefore, Table 4.2 presents the percentage changes in death per degree Celsius in indoor and outdoor environments. Even if the results are not directly comparable due to the different breakpoints, the outcomes tend to show higher values in indoor environments. Especially at indoor minimum temperatures, the percentage change in death per degree Celsius is far above that outdoors after the breakpoint and hence at heat stress levels. However, the clear tendency for higher risk rates and a higher percentage change in death in indoor environments have to be taken precautions, because the results are not significant.

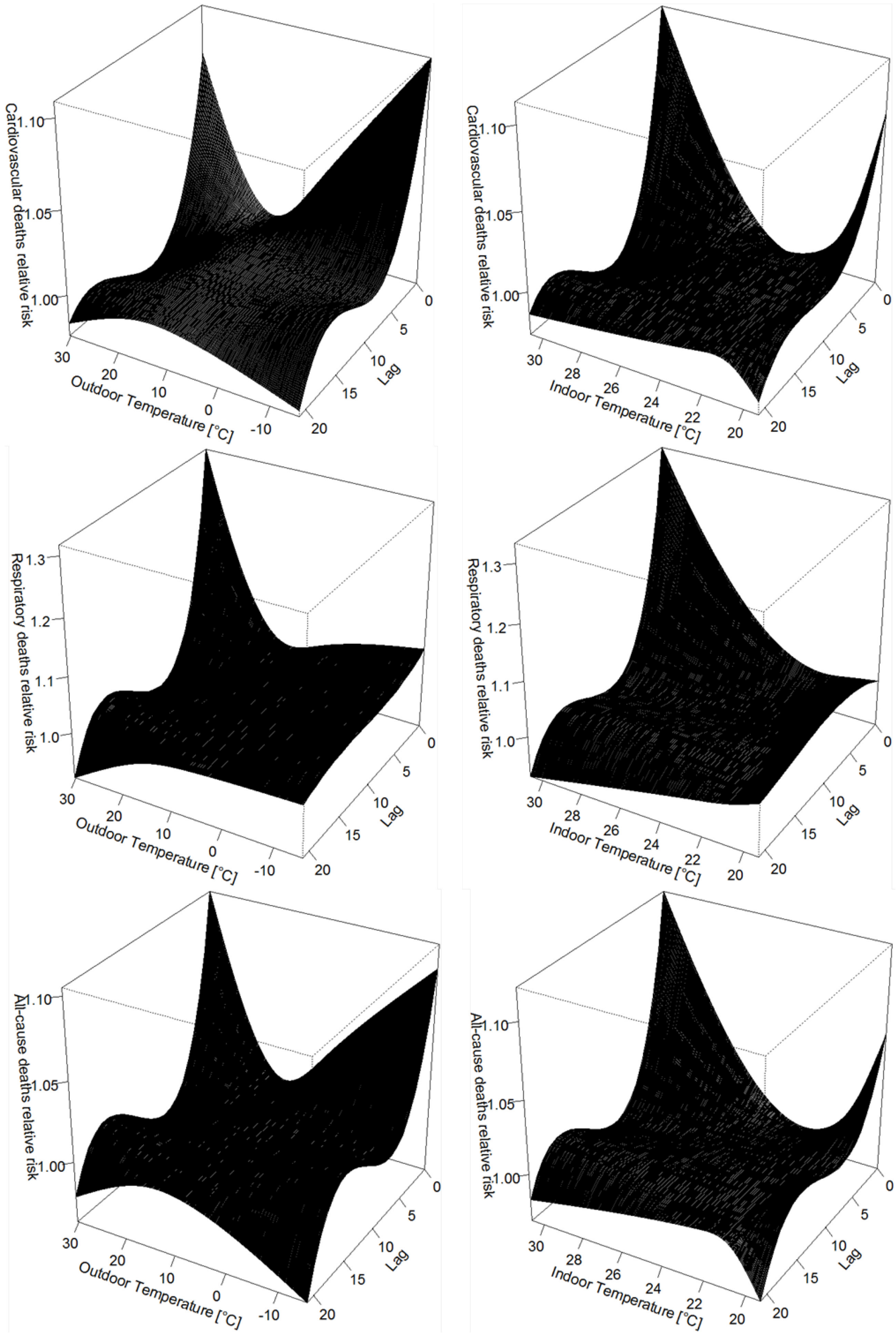

Figure 4.6 The estimated relative risk for cardiovascular, respiratory and all-cause mortality in Indoor and outdoor environments (Ta_mean) over 21 lagged days

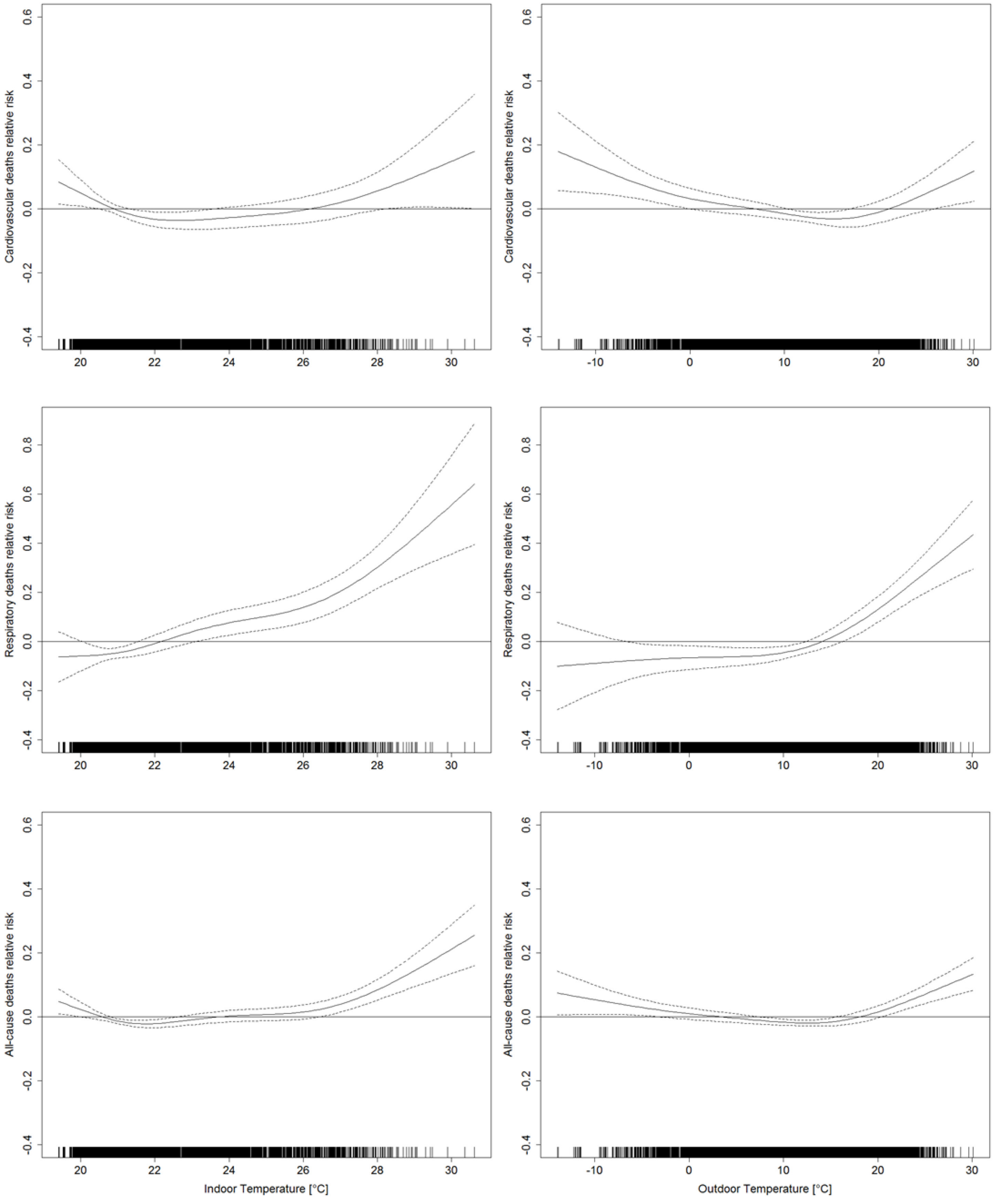

Figure 4.7 Exposure-response curves for daily cardiovascular (a), respiratory (b) and all-cause (c) mortality based on indoor (left) and outdoor (right) **mean** air temperature. Dashed lines indicate 95 % confidence intervals.

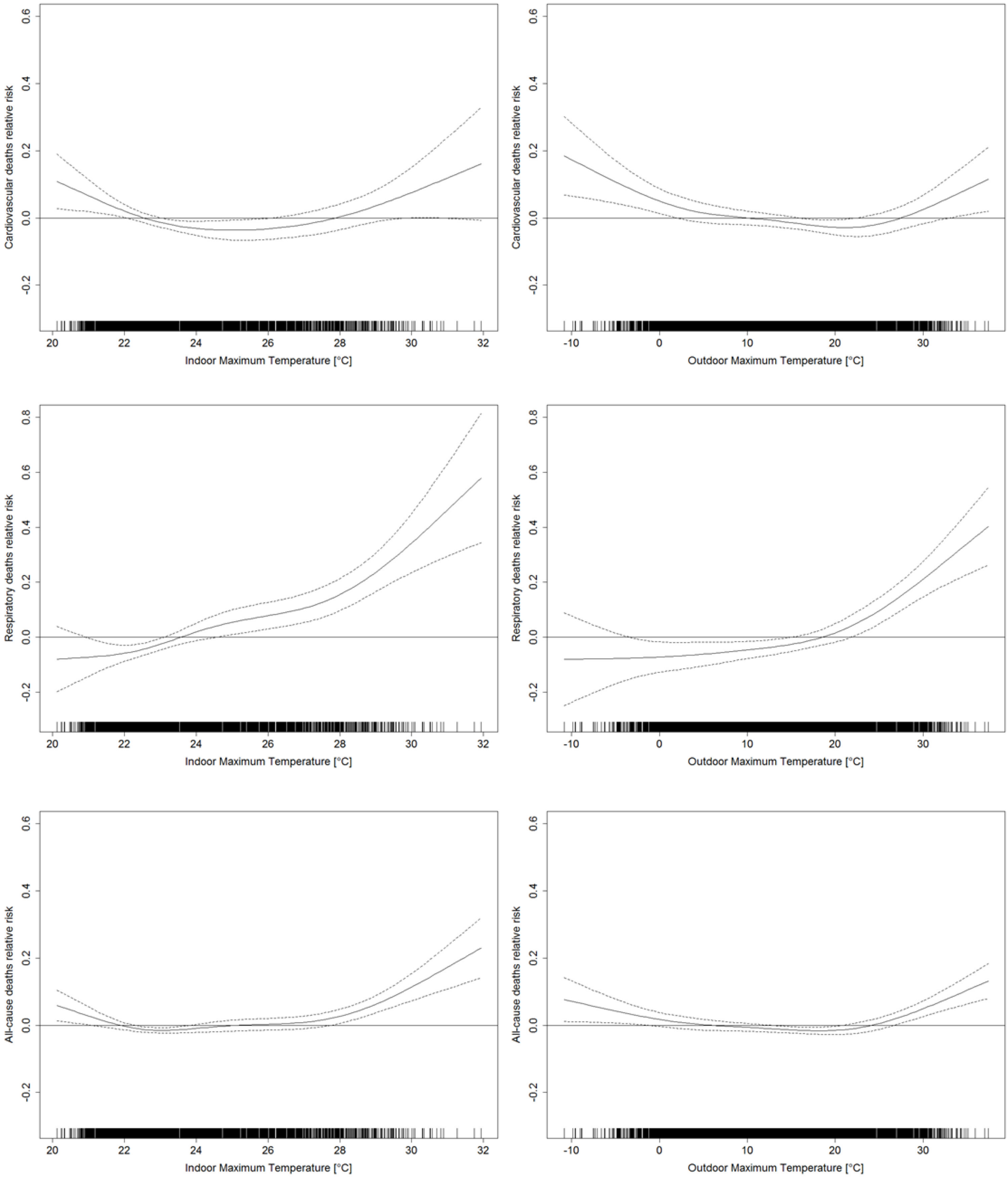

Figure 4.8 Exposure-response curves for daily cardiovascular (a), respiratory (b) and all-cause (c) mortality based on indoor (left) and outdoor (right) **maximum** air temperature. Dashed lines indicate 95 % confidence intervals.

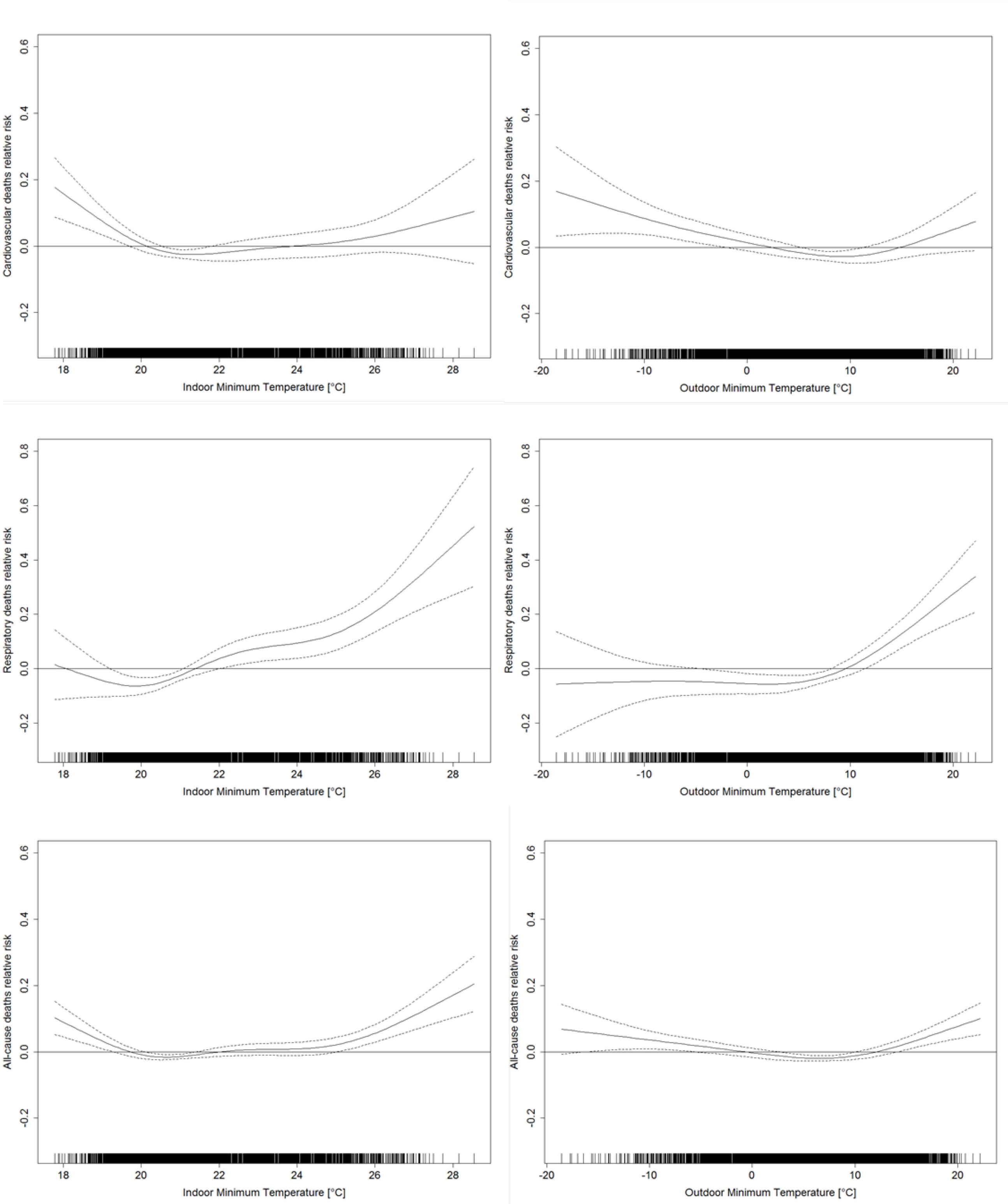

Figure 4.9 Exposure-response curves for daily cardiovascular (a), respiratory (b) and all-cause (c) mortality based on indoor (left) and outdoor (right**) minimum** air temperature. Dashed lines indicate 95 % confidence intervals.

Table 4.2 Percent Change in Deaths (95 % Confidence Interval) per Degree Celsius Increase in Temperature after the individual model breakpoint; * significant; dashed boxes presents higher percentage rates indoors

	Breakpoint		mean (1)		max (2)		min (3)	
	Indoor	Outdoor	Indoor	Outdoor	Indoor	Outdoor	Indoor	Outdoor
Cardio-vascular	23.9 (1) 26.1 (2) 21.0 (3)	18.0 (1) 24.6 (2) 8.1 (3)	*2.2 (0.6 to 3.8)	*1.1 (0.2 to 2.0)	*2.9 (1.0 to 4.9)	1.2 (0.3 to 2.1)	0.9 (-0.2 to 1.9)	0.5 (-0.1 to 1.1)
Respira-tory	27.7 (1) 29.8 (2) 26.8 (3)	7.3 (1) 23.4 (2) 4.4 (3)	12.5 (-0.4 to 27.0)	*1.5 (1.0 to 2.1)	18.7 (-1.8 to 43.5)	*1.9 (0.8 to 3.0)	*32.8 (3.3 to 70.6)	*1.7 (0.9 to 2.4)
All-cause	24.1 (1) 23.2 (2) 25.8 (3)	18.2 (1) 21.7 (2) 17.2 (3)	*1.8 (0.9 to 2.7)	*1.0 (0.5 to 1.5)	*1.0 (0.6 to 1.5)	*0.7 (0.3 to 1.0)	*7.2 (3.0 to 11.7)	*4.2 (1.9 to 6.7)

4.4 Discussion

Indoor climate and heat stress are important issues for human health. The potential increase in the frequency and intensity of heat waves is especially likely to affect chronically ill and vulnerable individuals, as they are mostly bound to staying indoors. Nevertheless, indoor environments are also likely to be relevant for the well-being and performance of healthy individuals, especially considering that modern society spends 90 % of the day indoors. So far, studies have mostly focused on heat stress risks in general, with no consideration of indoor environments. In contrast, the few existing indoor studies used detailed and complex indoor measurements for their analyses, which are not applicable for quantitative studies assessing health effects. In this paper, we analyzed whether outdoor temperature is an adequate measure to assess indoor climate in general and heat stress in particular. We tried to accommodate the need for adequately accounting for exposure, which mostly occurs indoors, but simultaneously provide a simple measure. So far, several studies have shown a profound relationship between outdoor temperature and mortality, as well as other health effects (Basu & Samet 2002, Baccini et al. 2008, Basu 2009, Gosling et al. 2009, Burkart et al. 2014).

The analysis of the relationship of measured outdoor and indoor temperature data was a prerequisite for the modeling of indoor data based on outdoor data. The results indicate a strong coherence between outdoor and indoor temperature, with no significant lag effects, which is consistent with other studies (Smargiassi et al. 2008, Nguyen et al. 2014, Quinn et al. 2014, Uejio et al. 2016). Indoor climate is mainly influenced by outdoor temperature, but it also depends on several other factors, such as building materials, exposition and user behavior (Vandentorren et al. 2006, Mavrogianni et al. 2012, Nguyen et al. 2014, Walikewitz et al. 2015b). Exposure times in indoor environments are longer, and adaptation measures are limited due to the confined indoor environment, e.g., working place or sleeping room, compared to outdoors, where locations can be changed. Using mean temperatures as predictors, we found no significant differences between indoor and outdoor values regarding temperature effects on mortality. Exposure-response curves were of similar shape, and the percentage change in mortality (0.8 %-1.6 %) was within the range of previous studies. Baccini et al. (2008) indicated an overall change in mortality with a 1 °C increase of approximately 1.8 % (0.1 %- 3.6 %) in the north-continental region. Monteiro et al. (2013) analyzed data from Portugal and found a 2.7 % (1.7 %- 3.6 %) increase in mortality. Based on these results, we conclude that mean outdoor and indoor air temperatures are equally good predictors of mortality.

Because we focused on indoor heat exposure during the day and night, we extended our research by considering the maximum and minimum temperatures. Maximum temperatures are usually lower indoors compared to outdoors due to the physical characteristics of the building (Höppe 1993). Due to the thermal inertness of solid materials, different construction materials result in different but always slower temperature increases compared to outdoor temperature. Furthermore, the important influence of direct solar radiation is limited indoors, whereas only shortwave radiation will directly enter a room while longwave radiation is completely absorbed by the outer side of the window (Frieß 2002). The analysis regarding the percentage change in death shows a higher risk for cardiovascular and respiratory cases at maximum indoor temperatures (Tab 4.2). Furthermore, lower UBRE-Scores of the GAMs indicate a slightly better model fit for indoor temperature as a predictor for respiratory and all-cause cases (Appendix Tab A.1). This may be explained with longer lasting extreme temperatures within indoor environments due to the thermal inertness of buildings (Wright et al. 2005). People experience longer exposures to the thermal thread, and elderly or other vulnerable people in particular are often limited in their mobility (Vandentorren et al. 2006, White-Newsome et al. 2012). This leads to the assumption that longer exposure times may hence be more important as the actual temperature peaks. However, the difference between the percentage changes are not significant and should therefore not be over-interpreted but kept in mind for further studies.

Minimum temperatures showed the biggest differences between indoor and outdoor environments; minimum indoor values were continuously above 17.7 °C and went up to 28.9 °C, whereas minimum outdoor values ranged from -18.9 °C to 22.9 °C (Fig 2). Indoor temperatures at night are markedly above outdoor temperatures, showing that buildings do not sufficiently cool down. Consequently, individuals are confronted with high nocturnal thermal loads in the indoor environment.

When looking at the analysis regarding the percentage change in deaths per degree Celsius increase (Tab 4.2) for minimum temperatures, we found similar results compared to maximum temperatures. Whereas outdoor temperatures are within the average range, the percentage change in death for indoor temperatures increases remarkably for respiratory (32.8 %) and all-cause (7.2 %) cases after the breakpoint. However, the results are not significant and have to be taken cautiously. Nevertheless, the results tend to show differences between indoor and outdoor environments and should therefore be discussed. The reasons for these differences can be manifold. The individual character of the buildings, such as differences in building material (e.g., solid brick or glass), the size of the building, as well as the urban structure in which the building is located are probably the main driving factors (Smargiassi et al. 2008, Franck et al. 2013). Additionally, the varying behavior of the residents as well as the general thermal inertness of buildings may contribute to this effect (White-Newsome et al. 2012, Franck et al. 2013). The impacts of the elevated indoor minimum temperatures may be considerable. In addition to a likely increased relative risk of death (Oudin Åström et al. 2011, Laaidi et al. 2012), non-fatal events such as a disturbed recovery phase at night due to decreasing sleep quality are likely (Libert et al. 1991, Bach et al. 1994, Okamoto-Mizuno & Tsuzuki 2010). Even though the results are not significant, indoor maximum and minimum temperatures should be considered in studies on heat stress and the health effects involved.

Regarding mortality displacement, we found no difference between indoor and outdoor environments. Identical to the studies of Basu and Ostro (2008), Bell et al. (2008), Michelozzi et al. (2009a), the results showed an immediate and strong effect of heat and suggested a more delayed effect for extremely hot temperatures. Furthermore, we found a small harvesting effect, especially above the 99 % percentile (Appendix Fig. A.1-A.6). However, the heat effect on all causes of death was more pronounced compared to the harvesting effect, and harvesting does not offset temperature effects.

Strengths and limitations

This study is one of the few studies assessing indoor heat stress risks. Most studies assessed indoor climate based on measurements that are either limited to a small number of study sites, describing just single rooms and not buildings, or have short measurement periods. In this study, we measured continuously over a period of two years within several different buildings and within different rooms regarding floor level in one building. We covered a wide range of construction types and possible driving factors of indoor climate, which increases the transferability to other settings, especially in Europe, where there is likely to be a greater similarity with regard to building types and urban structure. Previous studies were mostly set in Northern America (White-Newsome et al. 2012, Nguyen et al. 2014, Quinn et al. 2014, Uejio et al. 2016). To our knowledge, this is the first study on the relationship between indoor and outdoor environments conducted in Europe that covers more than a single heat event.

Nevertheless, there are some limitations that need to be acknowledged. Due to different time series of the climate and mortality data-sets and because of the long study period of ten years, we were not able to conduct the analysis with measured indoor data. The modeled indoor data might insufficiently reflect indoor conditions. For future research, we would like to extend this study by acquiring more mortality data within the actual indoor measurement period to overcome this limitation and to review the results of this study.

4.5 Conclusion

This study demonstrates a consistent and significant relationship between indoor and outdoor maximum, mean and minimum temperatures. We conclude that the outdoor temperature is an adequate measure to assess indoor heat exposure and the resulting health effects. Since the frequency and intensity of heat waves as well as summer temperatures in general are likely to increase in the coming decades, the need for an easy measure to assess heat stress is obvious.

Nevertheless, the study tends to show differences regarding the percentage change in death and the relative risk of death at maximum and minimum temperatures. Especially during the night, indoor temperatures stay at an elevated level, whereas outdoor temperatures decrease.

Hence, the thermal load is higher in indoor environments, and therefore, it is likely that the relative risk of death increases too. However, the results are not significant and further research is needed. In particular, longer time series with measured indoor temperatures are reasonable. Additionally, the increasing average age of the population and hence higher numbers of vulnerable people, which are mostly bound to indoor environments, underlines the need for more studies on this topic.

Acknowledgments

We would like to thank the German Research Foundation (DFG) for funding the Research Unit 1736 “Urban Climate and Heat stress in mid-latitude cities in view of climate change (UCaHS)” (EN138/21-1).

CHAPTER 5: SYNTHESIS

5.1 Main findings

The main aim of this thesis is to improve the understanding of indoor climate and indoor heat stress in particular. Moreover, the main driving factors as well as the variability of indoor heat stress in different buildings are investigated with a specific focus on urban climate. The study also discusses an application of the assessment of indoor heat exposure. A number of specific research questions were addressed, which constituted the subject matter of Chapters 2-4. While the research objectives of each individual chapter were explicit in nature, this synthesis employs a more integrative approach to elaborate upon the general research questions. The introduction to this thesis formulats three general research objectives.

Research objective 1:

Assessment of indoor climate regarding specific meteorological variables, measurement set-up as well as measurement devices

Heat stress can be described in detail through the four meteorological variables air temperature, mean radiant temperature, air velocity and relative humidity because these variables are essential for calculations involving the heat balance equation. Even if these detailed calculations require more input variables, heat balance models highlight the stages involved in understanding the relationship between thermal environments and human thermal perception. Indoor climate depends on the same meteorological variables as outdoor climate. However, indoor climate is driven by outdoor climate and is subject to manifold human influences. The diurnal course of indoor air temperature is dampened, as indicated by the lower average values during day and higher values during night. This dampening is due to an effect of the heat transfer resistance of the walls as well as their heat capacity as passive systems. Night-time is a particularly important consideration during heat waves in the context of the recovery phase during night and the resulting ability to cope with heat stress during the following day. The findings of the thesis show that the mean radiant temperature cannot be set equal to air temperatures at any time as performed in previous studies (Matzarakis & Amelung 2008, Kántor & Unger 2011, Langner et al. 2013). The difference between the two parameters is negligible under moderate outdoor conditions. Indoor air temperatures and the mean radiant temperature, however, differ at air temperatures above average in rooms with south-east and south-west exposed window walls and hence a high amount of direct solar radiation. The surrounding walls differ in surface temperatures, and the radiation fluxes are not uniform. The size and exposition of the window and the intensity and duration of direct solar radiation entering a room or hitting the surface are identified as the driving factors of the difference between Ta and Tmrt. In conclusion, the measurement of the mean radiant temperature is essential in studies of indoor heat stress and should not be neglected. With respect to measurement devices, this study reveals that there are no significant differences between detailed integral radiation measurement and more simplified globe thermometers.

The variable air velocity is an essential consideration in convective heat exchange between the human body and the ambient air. In outdoor environments, particularly during hot periods, air velocity or wind is an essential factor in convective heat loss. On hot summer days, a moderate wind can increase heat exchange and provide some cooling effect by reducing the mean skin temperature. The influence of air velocity on the heat transfer coefficient is not linear but resembles a root function (Höppe 1993). Thus, at very low air velocities, small changes have larger effects on convective heat transfer and, consequently, the mean skin temperature than the same small changes at high air velocities. Air velocity in enclosed spaces is commonly between 0.00 m/s and 0.20 m/s, whereas in naturally ventilated rooms with closed windows, the air velocity rarely exceeds 0.1 m/s (Höppe 2002). In artificially ventilated rooms, the air velocity tends to be higher and more turbulent. The role of turbulence in the air current on the heat transfer coefficient remains a matter of scientific discussion, but there are indications that high turbulence increases convective heat loss significantly. Although air conditioning is not common in Germany, air velocity was measured in this thesis due to its influence on convective heat loss in general. Measurement were conducted every 5 minutes using a hot-wire anemometer to include even small changes. However, no satisfactory way of measuring this variable was identified due to its high variability, and 0.00 m/s was the predominant measurement result. During heat waves, the results showed an increase in air velocity in some rooms of up to 0.7 m/s and higher, mainly due to open windows and doors. However, calculating the mean values for the assessment of indoor heat stress misses air velocity peaks and hence valuable information about heat stress in indoor environments. Sonic anemometers with higher resolution in time and measurement values would overcome this problem and provide more detailed information about the possible influence of indoor air velocity on heat stress.

Humidity can be expressed in an absolute and a relative way. The relative humidity is given as the ratio of the actual vapor pressure and the saturation vapor pressure, which is an exponential function of the air temperature. The humidity of the ambient air has many effects on the energy and water balance of the body. Three different routes of water loss from the body are influenced by the humidity of the ambient air: diffusion of water vapor through the skin, evaporation of sweat from the skin surface, and humidification of the respired air. In all cases, water is lost in gaseous form, results in energy loss from the body due to evaporation and hence a cooling effect (Melikov et al. 2013). If the ambient air at high air temperatures is saturated with water vapor, this cooling effect is diminished. The thermoregulation system attempts to reduce the thermal load through sweating, but the high relative humidity restrains this effect. Consequently, sultry environments are perceived as very uncomfortable compared to dry environments and can even cause health problems due to overheating of the body. With respect to the individual influences of the four meteorological variables, relative humidity is not considered in this thesis. However, the calculation of the UTCI requires this variable and hence considers the possible health effect during heat waves. Therefore, relative humidity was measured and is consequently considered within Chapter 3 and discussed within research objective 2. In Chapter 4, a general additive model was fit to investigate thermal effects based on air temperature on cardiovascular, respiratory and all-cause mortality. Sensitivity analysis of the model revealed no significant effect of relative humidity on mortality. Nevertheless, humidity influences the thermoregulation system and should therefore be considered in studies focusing on heat stress and health effects.

Research objective 2:

Assessment of the variability of indoor heat stress

Indoor heat stress is a severe threat to human health as noted previously in Chapter 1. Previous studies of indoor climate during summer temperatures have noted differences between indoor environments depending on the position within a building and between buildings (Beizaee et al. 2013, Quinn et al. 2014, Pathan et al. 2017). However, these studies have focused on one summer heat event or only covered several summer days per year, and thus their conclusions on the driving factors of variability are not verified. This thesis verifies outdoor climate as the main driving factor of indoor climate. In particular, the first part of Chapter 4 focused on this topic and indicates a strong coherence between outdoor and indoor temperature with no significant lag effects. The diurnal course of indoor temperature is dampened, as indicated by average lower values during day and higher values during night, but the overall relationship is consistent. The reasons for the variability of indoor heat stress are hence manifold and discussed within Chapters 3 and 4. No significant correlations were observed between indoor heat stress and different building characteristics. However, at some study sites, indoor heat stress was specified by a combination of more than one building characteristic, such as floor level, size of the window and year of construction. High correlations were, for example, observed in the top floors of modern buildings with large window areas, indicating a large impact of direct sunlight on indoor climate. The construction material of the building is also an important consideration. The results indicate higher heat stress levels in buildings with lightweight construction compared to buildings with thick solid stone walls, even when the buildings were constructed within the same year. This solid type of walls has a lower heat transmission coefficient than glass (Schulze 2004), and the rooms within the building require more time to warm and cool, as evidenced by a pronounced lag effect and, on average, lower heat stress levels. In conclusion, building characteristics are an important driving factor of indoor climate. However, this thesis reveals no clear pattern regarding the strength of each individual characteristic. Moreover, specific combinations likely lead to higher heat stress levels or compensation.

The results in Chapter 3 indicated that user behavior is another possible driving factor of the variability of indoor heat stress. The measurement concept of the thesis did not consider the influence of human behavior within the study. A questionnaire study was planned to detect the activity inside the study rooms but unfortunately was not conducted due to the limited ability of the users to provide valid information (e.g., users with dementia, students). However, the results for some study sites indicate a possible influence of user behavior, which therefore should be considered within the thesis. The outcomes for the retirement home are particularly noticeable. Heat stress levels decreased with increasing floor level. This effect is likely due to the behavior of the people within the rooms. At the highest floor, the person was aware of heat stress risks and took measures to reduce it, whereas the person at the lowest floor was bedridden and hence unable to apply any measures. Another example is heat stress variability within the public school. During the first heat wave, summer holidays started, and no measures to reduce heat stress were taken; the thermal load lasted for several days after the event. After the next heat event, the lag effect was less pronounced due to the influence of user behavior during school days. Although these examples provide no significant results, it is likely that user behavior is an important factor regarding the variability of indoor heat stress and should therefore be considered.

Research objective 3:

Assessment of the effect of indoor vs. outdoor temperature on indoor heat exposure

Knowledge of and, in particular, methods to assess indoor heat stress must be improved because people in modern society spend 90 % of the day in confined spaces. Chronically ill and vulnerable individuals may even spend up to 100 % of the day indoors due to their limited mobility. Hence, indoor climate is the main climate they are exposed to. The IPCC has projected that it is very likely that the frequency, duration and/or intensity of heat waves will increase in urban areas of Europe as a result of climate change (IPCC 2013a). Chapter 2 and 3 quantified indoor heat stress and indicated that it is already a severe threat during day and night. The projected amplification of heat stress due to climate change highlights the need for adequate measures to assess indoor heat exposure. Indoor climate measurements are essential to identify characteristics such as the distribution and variability of indoor heat stress. However, these measurements are very elaborate, costly and not regularly conducted by any public authority, in contrast to outdoor climate measurements. Studies focusing on, for example, adaptation or mitigation possibilities to reduce the thermal load would hence benefit from more simple measurement methods. Chapter 4 analyzed whether outdoor temperature is an adequate measure for assessing indoor heat exposure. Outdoor data are usually easily accessible, intensely measured and standardized. The risk of heat waves for human health has been thoroughly investigated, and the link between elevated outdoor temperatures and mortality rates is widely accepted in the scientific community. However, uncertainties remain, and this thesis attempts to estimate whether indoor air temperature is a better predictor of mortality. The results showed no difference between the mean indoor and outdoor air temperatures. The exposure-response curves were similar in shape, and the percentage change in mortality was within the range of previous studies. Because the focus of this chapter is on indoor heat exposure during day and night, maximum and minimum temperatures are also considered.

Maximum temperatures are usually lower indoors compared to outdoors due to the physical characteristics of the building (Chapter 1). Different construction materials result in different but always slower temperature increases compared to outdoors due to the thermal inertness of solid materials. Furthermore, the important influence of direct solar radiation is limited indoors; only short-wave radiation will directly enter a room, whereas long-wave radiation is completely absorbed at the outdoor side of the window. The analysis of the percentage change in death per degree Celsius increase revealed higher risks of cardiovascular and respiratory death at maximum indoor temperatures (Chapter 4). This increased risk may be explained by the longer persistence of extreme temperatures within indoor environments due to the thermal inertness of buildings. People are exposed longer to the thermal thread, particularly the elderly or other vulnerable people with limited mobility. This finding leads to the assumption that longer exposure times may be more important than the actual temperature peaks. However, the results are not significant and should therefore not be over-interpreted but kept in mind for further studies.

The largest differences between indoor and outdoor environments were observed in the minimum temperatures. Indoor temperatures during night were markedly higher than the outdoor temperatures, revealing insufficient cooling of the buildings. Consequently, individuals are confronted with high nocturnal thermal loads in the indoor environment. The analysis of the percentage change in death per degree Celsius increase in minimum temperatures revealed results similar to those for the maximum temperatures. The percentage change in death indoors increased remarkably for respiratory and all-cause cases at elevated indoor temperatures. Although the results were, again, not significant, they reveal tendencies in the differences between indoor and outdoor environments and should therefore be discussed. The reasons for these differences may be manifold. The individual characteristics of the buildings, such as building material (e.g., solid brick or glass), size and the urban structure the building is located in, are probably the main driving factors. Additionally, the varying behaviors of the residents as well as the general thermal inertness of buildings may contribute to this effect. The impacts of the elevated indoor minimum temperatures may be considerable. In addition to a likely increased relative risk of death, non-fatal events such as a disturbed recovery phase at night due to decreased sleep quality are likely. Although the results are not significant, indoor maximum and minimum temperatures should be considered in studies of exposure times of heat stress and related health effects.

5.2 Limitations of the work

Few studies have explored heat stress in indoor environments in urban areas and this thesis represents a substantial contribution to a much improved understanding of the relationship between indoor and outdoor climate as well as the driving factors of indoor heat stress. The analysis was based on continuous measurement data from summer 2013 to summer 2015. The measurement set-up covered a wide range of building types and different urban areas. Furthermore, the meteorological variables air temperature, mean radiant temperature, air velocity and relative humidity were measured, which is relatively unique for indoor measurements and covers all essential input parameters for the assessment of heat stress. Nevertheless, the data used in this study represent only a sample of buildings and do not completely represent the diversity of a city. Furthermore, it was not possible to measure all meteorological variables at all study sites. For instance, when the measurement devices were installed in classrooms at a public school, only small and inconspicuous devices such as the air temperature and relative humidity instruments were installed due to the threat of vandalism. At study sites where only the small measurement set-up could be installed, the mean radiant temperature was set equal to the air temperature, and the air velocity was set equal to zero based on measurement experience. Additionally, the measurement devices for air velocity were not as precise as assumed. The chosen hot-wire anemometer was not able to measure at higher time resolution. Consequently, the air velocity between the 5-minute measurement intervals was not considered. Compared to air temperature, mean radiant temperature and relative humidity, air velocity is highly variable. For instance, the opening of windows leads to a sudden increase within seconds and stops immediately after the window is closed. If this action is not captured by the measurement device, valuable information is lost. In particular, increased air velocity is often noted for its soothing effect during unfavorable thermal conditions and heat stress. In indoor environments, the reduction of heat stress due to an increment of air velocity is mostly attributable to the actions of the users. The results of Chapter 3 emphasize that user behavior is an important consideration and very likely a driving factor of indoor heat stress. Unfortunately, the study did not consider user behavior in a quantitative and qualitative manner. The planned questionnaire study could not be conducted due to limited user presence (holidays) and the limited ability of the users to provide valid information (e.g., people with dementia). The shortage of nursing staff in the retirement homes prevented a questionnaire study of the employees. However, the study detected a strong tendency of the importance of user behavior even though the results were not significant.

The use of the UTCI in indoor environments requires some explanation. The UTCI was developed and evaluated for outdoor conditions and hence is not applicable indoors. However, when describing indoor heat stress, it is important to consider outdoor conditions. Furthermore, the study was built on all relevant meteorological parameters influencing human bioclimate and not air temperature alone. It is therefore necessary to use a rational index with a thermal comfort model and further consider human physiology, as well as the influence of clothing. The current use of the UTCI in indoor environments has some limitations pertinent to this study. First, the air velocity was not within the range of validation for the UTCI calculation. This increase in air velocity may have led to an underestimation of heat stress because higher levels reduce the thermal load within the UTCI calculation. Second, when the activity of a person is above average indoor levels corresponding to a sitting position as the main activity, the determination will likely lead to an overestimation of heat stress due to higher internal heat production and hence higher thermo-physiological model output. A first attempt to overcome some limitations regarding different activity levels and exposure times was introduced in Chapter 3, and the results showed lower UTCI values on average at all sites. The UTCI correction terms employed here consider activity at a resting level and exposure duration covering an 8-h shift length to reflect indoor conditions. However, the results did not include a modification regarding air velocity. Due to the incompleteness and missing evaluation of this UTCI adaptation for indoor environments, the correction terms are not considered in the analysis.

Another limitation of the study is the use of calculated indoor data for the analysis in Chapter 4. Indoor data were measured from summer 2013 to summer 2015, whereas mortality data were only available from 2000 to 2010. To obtain indoor data for the same period, the relationship between indoor and outdoor data was analyzed and subsequently used to calculate indoor data based on outdoor data. The differences between indoor and outdoor temperatures as predictors for mortality were subsequently investigated. The use of this method entails the caveat that a certain relationship between indoor and outdoor data is obvious, and further analysis with mortality data during the indoor measurement period is necessary to confirm the results of this chapter.

5.3 Conclusion and perspectives

For the first objective, a comprehensive measurement campaign for indoor climate parameters was conducted to investigate the relationship between air temperature and the mean radiant temperature as well as to examine possible influences on these parameters under warm conditions. The results confirmed that the difference between the two parameters is negligible under moderate outdoor conditions. However, the two parameters revealed differences at air temperatures above average in rooms with south-east and south-west exposed window walls. The surrounding walls differed in surface temperatures, and the radiation fluxes were not uniform. The size and exposition of the window and the intensity and duration of direct solar radiation entering a room or hitting the surface were identified as driving factors of the difference between air temperature and the mean radiant temperature. To verify the findings, a dynamic simulation covering the same period as the instrumental measurements should be conducted. Furthermore, the same analysis should be conducted in different buildings with varying materials. Prospective studies investigating indoor climates during high outdoor temperatures or even heat waves are recommended to examine the mean radiant temperature. This parameter is required to calculate thermal indices that are widely used in heat stress studies. If the mean radiant temperature is made equivalent to the air temperature, indoor heat stress may be underestimated, and the wrong conclusion regarding human health may be obtained.

The second objective was to examine the spatial and temporal variability of indoor heat stress. A detailed measurement system was established covering two complete years of indoor climate based on measurements of air temperature and relative humidity and measured or modeled data on mean radiant temperature and air velocity. Based on the calculated UTCI levels, all rooms experienced heat stress especially during heat waves. Heat stress occurred on 34 % of all days in summer 2013 and 2014 either during day or at night. During heat waves, heat stress at night is higher indoors than outdoors due to the thermal inertness of buildings. As a consequence, the recovery phase during night is disturbed, and the ability to cope with heat stress during the next day will likely be decreased. The results for the driving factors of indoor climate confirm those of previous studies by showing that indoor climate is mainly driven by outdoor climate. Another worthwhile research objective may be the analysis of user behavior as a driving factor. The ascertainment of user behavior is complex and beyond the scope of this thesis. However, an understanding of how the behavior or specific actions of users influence indoor heat stress will ultimately permit the assessment of different adaptation strategies to reduce indoor heat stress. Another possible future research area is the adaptation of the UTCI to indoor environments. Rational indices are essential for the detailed assessment of heat stress on the human body. The UTCI comprises the most up-to-date clothing model with a multi-node model of human heat transfer and temperature regulation. A first attempt was conducted in this thesis. In addition to adaptation of the activity level and exposure times, the modification of air velocity within the calculation procedures is essential. Moreover, the UTCI and other indices are determined for a standardized individual of middle age and average height and weight. However, those in danger of dying from heat are most likely to be older or younger or suffer from serious and long-term medical conditions. Extending the UTCI in this regard would represent a valuable research task with considerable potential for improving its applicability in indoor heat stress assessment.

As the third objective, the relationship between outdoor temperature and indoor temperature using data from the indoor measurement system was analyzed. The results demonstrated a consistent and significant relationship between indoor and outdoor maximum, mean and minimum temperatures, thus concluding that outdoor temperature is an adequate measure to assess indoor heat exposure and the resulting health effects. Nevertheless, the study showed a tendency of differences in the percentage change in death and the relative risk of death at the maximum and minimum temperatures. In particular during night, indoor temperatures remain elevated, whereas outdoors temperatures decrease. Hence, the thermal load is higher in indoor environments, and therefore it is likely that the relative risk of death also increases. However, the results are not significant, and further research is needed. Longer time series with measurement of indoor temperatures are reasonable. Furthermore, this thesis did not consider the association between indoor and outdoor temperature and morbidity. Previous studies have shown that morbidity increases with increasing outdoor temperature. However, the results show a more distant relationship with mortality; consequently outdoor temperature is not sufficient to predict morbidity and other driving factors must be approved. A new research perspective could hence be the predictive power of indoor climate for morbidity. Because modern society spends more than 90 % of their day in confined spaces, indoor climate may be a main driver of morbidity. Other less severe health impacts should also be considered, such as fatigue and reduced concentration.

Based on a number of new and relevant findings, this thesis indicates that indoor heat stress is a major hazard. Due to the global increase in air temperature, the frequency and intensity of heat waves as well as summer temperatures in general will likely increase in the coming decades. The increasing average age of the population and hence higher numbers of vulnerable people who are mostly confined to indoor environments emphasize the need for more studies on this topic. Further effort in understanding the causes of indoor heat and creating effective countermeasures is therefore essential.

APPENDIX

Supplementary material provided with the manuscript "Walikewitz N., Burkart K., Endlicher W. (2017): Analysis of outdoor air temperature as an adequate measure to assess indoor heat exposure. The Science of the Total Environment (submitted)"

Table A.1 UBRE-Scores for the generalized additive models regarding temperature and cause of death; grey boxes indicate a better model fit

Temperature	mean		max		min	
	Indoor	Outdoor	Indoor	Outdoor	Indoor	Outdoor
Cardiovascular	0.08939	0.088162	0.88872	0.88792	0.08813	0.088149
Respiratory	0.13779	0.13841	0.1389	0.13962	0.14156	0.14268
All-cause	0.26778	0.26885	0.26861	0.27015	0.2687	0.27083

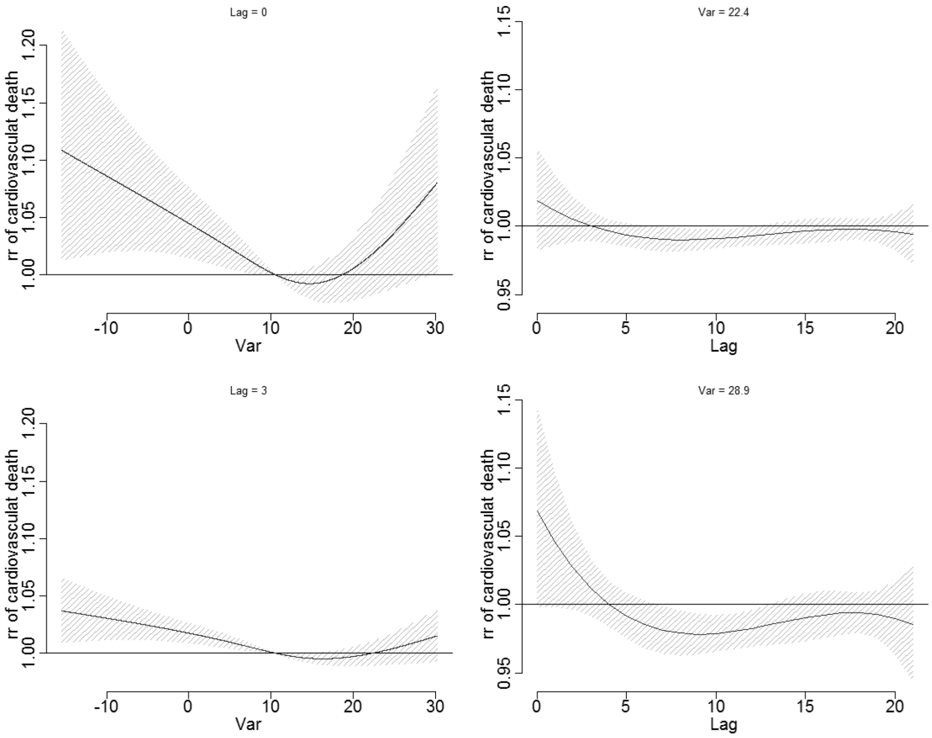

Figure A.1 Relative risk of **cardiovascular deaths** by temperature (var) at specific lags (left) and by lag at the 95th (top) and 99.9th (bottom) percentiles of **outdoor temperature** distribution (right)

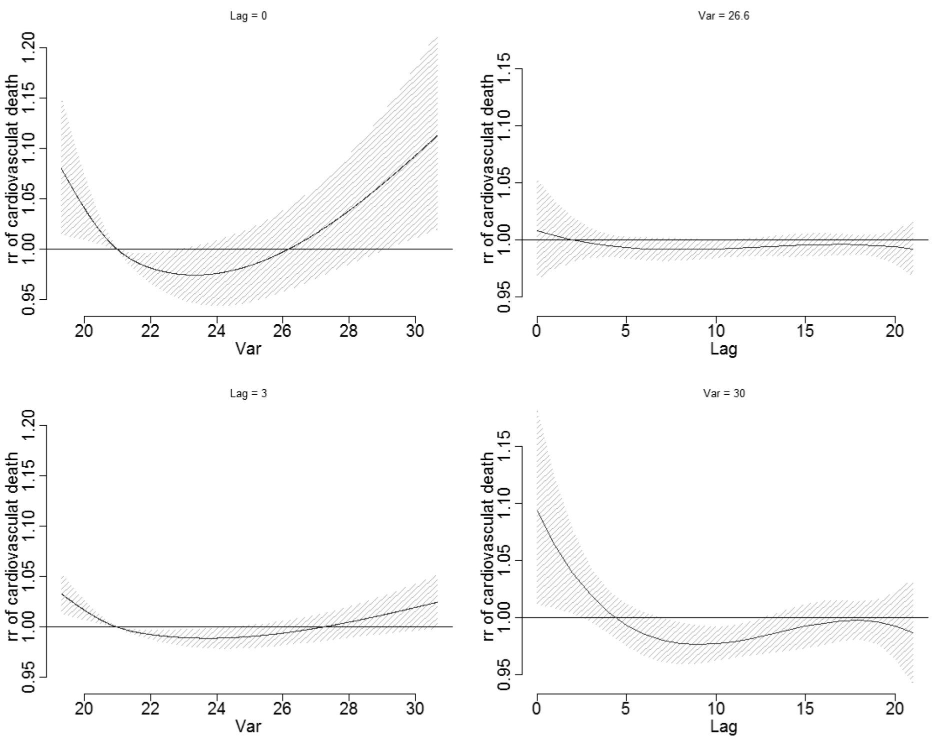

Figure A.2 Relative risk of **cardiovascular deaths** by temperature (var) at specific lags (left) and by lag at the 95th and 99.9th percentiles of **indoor temperature** distribution (right)

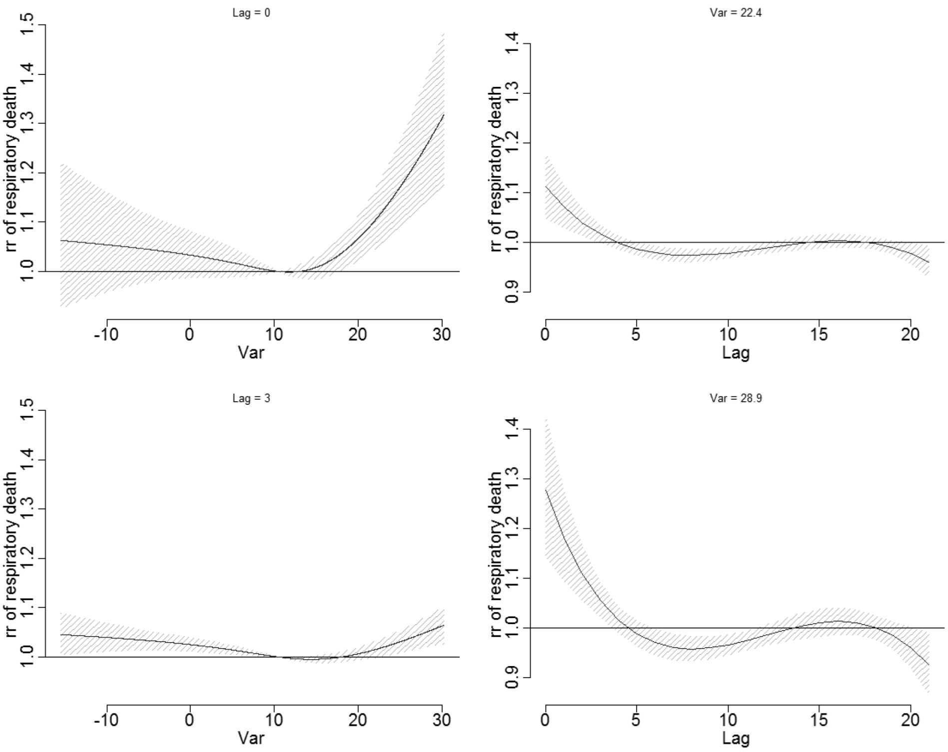

Figure A.3 Relative risk of **respiratory deaths** by temperature (var) at specific lags (left) and by lag at the 95th and 99.9th percentiles of **outdoor temperature** distribution (right)

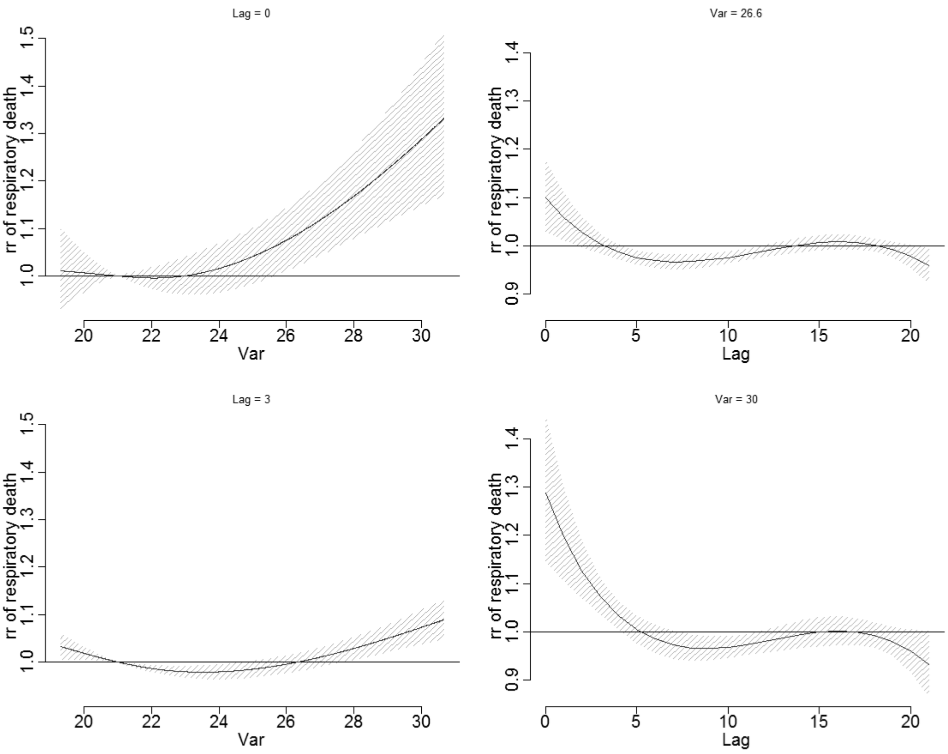

Figure A.4 Relative risk of **respiratory deaths** by temperature (var) at specific lags (left) and by lag at the 95th and 99.9th percentiles of **indoor temperature** distribution (right)

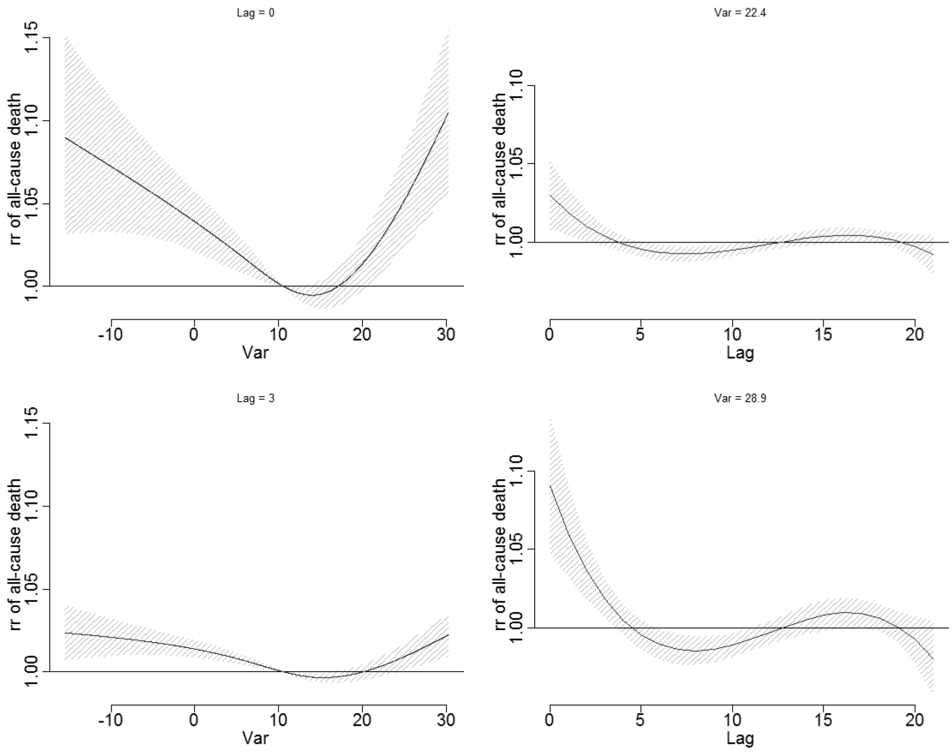

Figure A.5 Relative risk of **all-cause deaths** by temperature (var) at specific lags (left) and by lag at the 95th and 99.9th percentiles of **outdoor temperature** distribution (right)

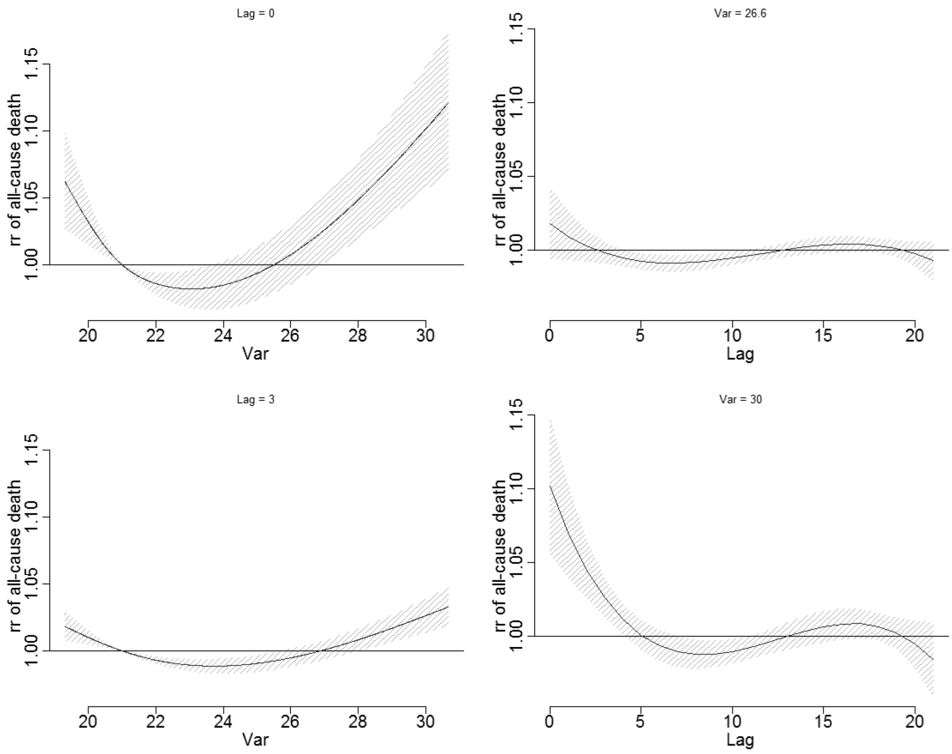

Figure A.6 Relative risk of **all-cause deaths** by temperature (var) at specific lags (left) and by lag at the 95th and 99.9th percentiles of **indoor temperature** distribution (right)

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Selbständigkeitserklärung gemäß §7 Absatz 4

„Ich erkläre, dass ich die Dissertation selbständig und nur unter Verwendung der von mir gemäß § 7 Abs. 3 der Promotionsordnung der Mathematisch-Naturwissenschaftlichen Fakultät, veröffentlicht im Amtlichen Mitteilungsblatt der Humboldt-Universität zu Berlin Nr. 126/2014 am 18.11.2014 angegebenen Hilfsmittel angefertigt habe.“

Berlin, den 29.05.2017

Nadine Walikewitz