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Indoor heat stress: An assessment of human bioclimate using the UTCI in different buildings in Berlin

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Abstract

Because humans spend most of their time indoors and can be negatively affected by unfavourable thermal environments, the assessment of indoor heat stress is an important issue for public health care. To characterise indoor human bioclimate, the Universal Thermal Climate Index (UTCI) was used. UTCI values were calculated from measurements of air temperature and air humidity in 16 rooms in Berlin during the summer months of 2011 and 2012. A constant air velocity of approximately 0.3 m/s and a metabolic heat production of 135 W/m² were assumed. The mean radiant temperature was set to the air temperature. Because the mean air humidity was below or slightly above 50 %, the calculated UTCI values were mostly lower than the air temperatures. In summer 2012, the mean UTCI values ranged from 22.2 °C to 27.1 °C, and the maximum UTCI values ranged from 24.7 °C to 35.6 °C. Whereas only minor differences were found between rooms located within comparable buildings in different districts of Berlin, pronounced variations of the UTCI values were detected in two adjoining buildings, with differences up to 8.6 K for the daily minimum, 9.8 K for the daily mean and 12.2 K for the daily maximum UTCI between different rooms. These variations can be explained by differences in the structures of the two buildings, floor level and aspect. The UTCI values were also used to determine the occurrence of moderate and strong heat stress. Only two rooms showed no thermal stress, while strong heat stress was detected in three rooms.

Zusammenfassung

Da Menschen die meiste Zeit in Innenräumen verbringen und ihre Gesundheit durch ungünstige thermische Bedingungen negativ beeinflusst werden kann, ist die Bewertung von Hitzestress in Innenräumen eine wichtige Aufgabe der öffentlichen Gesundheitsvorsorge. Um das Human-Bioklima in Innenräumen zu charakterisieren, wurde der Universal Thermal Climate Index (UTCI) verwendet. Die Werte des UTCI wurden aus Werten der Lufttemperatur und Luftfeuchte berechnet, die während der Sommermonate 2011 und 2012 in 16 Räumen in Berlin gemessen wurden. Zur Berechnung wurden eine konstante Luftbewegung von ca. 0,3 m/s und eine metabolische Wärmeproduktion von 135 W/m² angenommen. Die mittlere Strahlungstemperatur wurde der Lufttemperatur gleich gesetzt. Da die mittlere Luftfeuchte unter oder leicht über 50 % lag, waren die berechneten Werte des UTCI zumeist kleiner als die Lufttemperatur. Im Sommer 2012 lagen die mittleren Werte des UTCI zwischen 22,2 °C und 27,1 °C und die maximalen Werte zwischen 24,7 °C und 35,6 °C. Während nur geringe Unterschiede zwischen Räumen in vergleichbaren Gebäuden in unterschiedlichen Berliner Bezirken gefunden wurden, ergaben sich ausgeprägte Unterschiede innerhalb zweier angrenzender Gebäude. Hier betrugen die Unterschiede zwischen zwei Räumen bis zu 8,6 K beim täglichen Minimum, 9.8 K beim täglichen

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Mittel und 12.2 K beim täglichen Maximum des UTCI. Diese Variationen können durch Unterschiede in der Struktur der beiden Gebäude, den Stockwerken und der Exposition der Räume erklärt werden. Die Werte des UTCI wurden ebenso verwendet, um das Auftreten von moderatem und starkem Hitzestress zu erfassen. Nur in zwei Räumen wurde kein thermischer Stress nachgewiesen, starker Hitzestress trat in drei Räumen auf.

Keywords Heat stress, indoor climate, UTCI, Berlin

1. Introduction

Urban agglomerations show altered radiative and heat fluxes compared to their rural surroundings. The most prominent effect of these modifications is a tendency toward higher air temperatures in urban areas, leading to the so-called urban heat island effect. Many factors govern the formation of the urban heat island, including an increase in the absorption of short-wave radiation and sensible heat storage and a decrease in long-wave radiation loss and evapotranspiration (*Oke* 1982). It is also assumed that the global increase in air temperature due to climate change will especially affect humans in urban environments (*Matzarakis* and *Endler* 2010). Therefore, heat stress caused by unfavourable thermal conditions can be regarded, in addition to air pollution and noise, as a serious environmental risk to humans in cities.

Several risks associated with heat stress have been identified. Many authors have found increased mortality rates caused by hot temperatures, especially during heat wave events, e.g., *Almeida* et al. (2013) in Oporto and Lisbon (Portugal), *Rocklov* et al. (2011) in Stockholm County (Sweden), *Gabriel* and *Endlicher* (2011) in Berlin (Germany) and *Kysely* (2004) in the Czech Republic. There is also evidence that heat stress has adverse effects on morbidity (*Michelozzi* et al. 2011, *Monteiro* et al. 2013). Many of the cited studies showed that elderly people, i.e., those older than 65 years, are particularly vulnerable to heat stress. Infants are also vulnerable, especially in the first week of life (*Basagana* et al. 2011). In addition to the influence of heat on human health, heat stress has adverse effects on human well-being, performance and mental awareness. Several studies have shown that increased temperatures affect tasks such as typewriting and signal recognition (*Lundgren* et al. 2013). Even a moderately elevated air temperature can lead to negative effects on office work performance (*Wyon* 2004). An increased temperature may also reduce the performance and attendance of students, although not all studies support these results (*Mendell* and *Heath* 2005). *Kjellstrom* and *McMichael* (2013) argued that climate change will have severe negative impacts on human well-being due to heat stress.

The thermal environment of humans is defined by six fundamental factors. They include four environmental factors (air temperature, mean radiant temperature, air humidity and air movement), the metabolic heat produced by human activity and the clothes a person wears (*Parsons* 2003). Whereas the last two factors may vary between persons due to acclimatisation, behaviour, gender, age and health status, the environmental factors can be regarded as objective parameters that act on every person at a certain point in space and time.

In a basic approach, air temperature can be used as an indicator to characterise the whole set of environmental factors. Many epidemiological studies have linked health outcomes to parameters of air temperature, such as the mean monthly temperature (*Fernandez-Raga* et al. 2010), the mean daily temperature (*Paldy* et al. 2005) or the maximum daily temperature (*Almeida* et al. 2013). Nevertheless, it is more appropriate to include additional factors in an analysis of the thermal environment of humans. This consideration is applied in human biometeorology by using thermal indices. Simple indices, such as the New Wind Chill Temperature, take into account only two factors. The New Wind Chill Temperature is based on air temperature and wind speed and intends to express the combined effects of these two factors on the cooling of exposed skin (*Osczevski* and *Bluestein* 2005). Whereas advanced indices such as the apparent temperature consider all four environmental factors (*Steadman* 1984), the most sophisticated indices cover the entire set of influencing factors. One common example is the PMV (Predicted Mean Vote), which quantifies the mean thermal sensation of humans as a function of all six fundamental factors and has been used in many outdoor and indoor environments (*Fanger* and *Toftum* 2002). Because the PMV predicts thermal sensation on a seven point ordinal scale, it may be difficult to interpret for practitioners such as urban planners and health care attendants, who are not familiar with biometeorology (*Mayer* and *Höppe* 1987). Therefore, it is preferable to present thermal indices on a familiar scale. One of these indices is the recently developed Universal Thermal Climate Index (UTCI). The UTCI was designed to quantify outdoor thermal conditions and is based on the concept of an equivalent temperature. Therefore, its values are expressed in units of °C. It gives an isothermal air temperature with respect to a reference environment that produces the same dynamic response from the human body (*Jendritzky* et al. 2012). The reference environment, regarding the meteorological parameters, was set to 50 % relative humidity (the water vapour pressure is not allowed to exceed 20 hPa), calm air and a mean radiant temperature equal to the air temperature. As a reference condition for the human activity, a walking speed of 4 km/h was chosen, that equals a metabolic heat production of 135 W/m^2 (*Bröde* et al. 2012). The UTCI is based on a multi-node model of human heat transfer and temperature regulation (*Fiala* et al. 2012) and a newly developed clothing model, which takes into account the typical dressing behaviour under different thermal outdoor conditions for a representative European and North American urban population (*Havenith* et al. 2012). A detailed description of the operational procedure to calculate the UTCI can be found in *Bröde* et al. (2012).

Most people, especially vulnerable people, spend their time mainly indoors during periods with unfavourable thermal conditions. Hence, the aim of this study is to characterise indoor thermal environments using the UTCI with a focus on heat stress. Although the UTCI was developed for outdoor conditions, it was used in this study for two main reasons to analyse indoor conditions. First, it allows the values to be put into different categories of thermal stress such as moderate and strong heat stress. Second, epidemiological studies, connecting meteorological data with health outcomes, typically use outdoor conditions, e.g., *Hartz* et al. (2013) analysed the influence of meteorological conditions on emergency dispatches with UTCI values derived from outdoor measurements. Therefore, it is important to characterise indoor thermal environments in a similar way to broaden our knowledge about the impact of heat stress on human health.

Because indoor heat stress may not only be governed by the outdoor atmospheric conditions but also by properties of the building or the location of a room within a building, several buildings and different rooms in Berlin were included in the study. The study also tested whether the urban heat island of Berlin has a notable effect on indoor thermal environments.

2. Sites and methods

2.1 Measurement sites

The measurements were carried out in various buildings in Berlin, Germany's capital. According to the latest census from 2011, Berlin has approximately 3.3 million inhabitants (Statistisches Bundesamt 2013). It covers an area of 892 km^2 and has many public green spaces (11 % of the area) and forests (18 % of the area) within its administrative borders (Amt für Statistik Berlin-Brandenburg 2012). Berlin is located in northeast Germany and lies in the North German Plain. Therefore, it has a rather flat topography, with the Barnim Plateau in the northeast and the Teltow Plateau in the south, flanking the Berlin-Warsaw Urstromtal, a broad valley formed during the last glaciation. The differences in topography amount to a few tens of metres, so topography has only a minor influence on the local climate. The higher parts have slightly increased air temperatures, but the differences due to topography are typically lower than 1 K (*Hendl* 2002). Berlin has a temperate climate with characteristics of both oceanic and continental influences. The yearly average air temperature ranged from 7 to 10.5 °C throughout Berlin and the surrounding areas for the period from 1961 to 1990 (Senatsverwaltung für Stadtentwicklung und Umwelt 2011). During the same period, the warmest recorded temperature was 35.8°C, and approximately 32 summer days and 6 hot days occurred per year at the weather station in Berlin-Dahlem (*Endlicher* and *Lanfer* 2003)[1].

The measurements were carried out in eight buildings located in different districts in Berlin (*Fig. 1*). The buildings vary in use from office buildings (O-1 to O-3) to a hospital (H-1), as well as residential buildings (R-1 to R-4). Five rooms were selected in the office buildings O-1 and O-2, which form a building complex hosting the Geography Department of the Humboldt-Universität. Measurements were performed in one room within the other buildings. The different buildings vary in use, age and the environment in which they were built. The concept of local climate zones (LCZ) is used to characterise these different construction environments in *Table 1*. The local climate zones can be used in urban temperature studies to describe the local settings with uniform characteristics such as surface cover or human activity, spanning a horizontal scale from hundreds of metres to several kilometres (*Stewart* and *Oke* 2012). The characteristics of the single rooms, such as the aspect of the exterior wall or the floor level, are

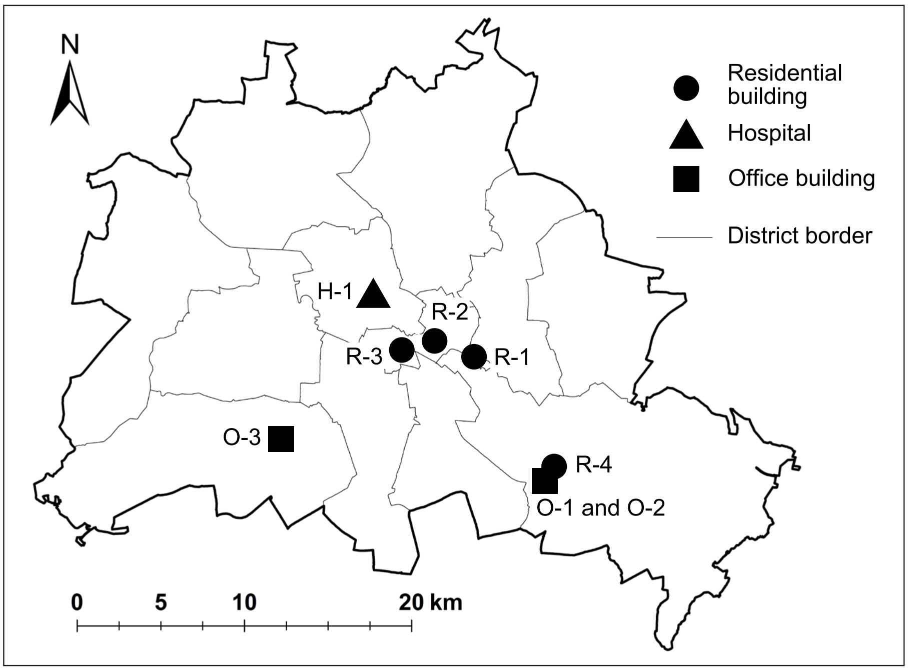

Fig. 1 The locations of the eight buildings in Berlin where the indoor measurements were carried out

also given in *Table 1*. None of the rooms are air-conditioned. Room O-2-1 has an active air ventilation system. Information about the construction material can be deduced from the age of the building. Whereas old buildings have been built with bricks, new buildings have been constructed with concrete. In addition, the façade of building O-2 is dominated by glass surfaces.

2.2 Methods

Each room was equipped with a HygroWin sensor from ROTRONIC (rotronic messgeräte gmbh, Germany). These sensors measure air temperature and air humidity with an accuracy of ± 0.5 °C and ± 3 %, respectively. They were used in a configuration that outputs their measurement signal through a serial interface. The sensors were mainly fixed at a height of approximately 2 m above the floor level in each room at a distance of approximately 3 cm to the adjoining wall. The sensors were placed at locations within the rooms where they would not be directly influenced by sunlight.

All sensors were connected to the Ethernet via NPort 5110 servers from Moxa (Moxa Inc., Taiwan) to provide online access to the measured data. A fixed IP address or, in case of private rooms in residential buildings, a dynamic DNS address, was assigned to the NPort servers. A server at the Department of Geography of the Humboldt-Universität collected the data using the EASYCOMP software (BREITFUSS Messtechnik GmbH, Germany). The sampling rate was set to one second. EASYCOMP was configured to store the values as minute averages in ASCII-formatted files.

The software BioKlima 2.6 (available from http://www.igipz.pan.pl/Bioklima-zgik.html) was used to determine the UTCI values as minute averages. To calculate the UTCI values from measured air temperature and air humidity using BioKlima 2.6, assumptions must be made about the mean radiant temperature and the air velocity. As proposed by *Matzarakis* and *Amelung* (2008) for an indoor environment, the mean radiant temperature was set to the air temperature. The same authors assumed a fixed air velocity of 0.1 m/s for an indoor reference climate. Unfortunately, 0.1 m/s is below the range of validity for the use of the regression function to calculate the UTCI. Therefore, an air velocity of 0.5 m/s at a level of 10 m above ground was used. This is the lowest value of air velocity that lies in the range of validity and corresponds to approximately 0.3 m/s at the level of a person's body (*Bröde* et al. 2012). The measured values of air temperature and air humidity were completely within the range of validity.

The measurements started in July 2010 in selected rooms. The measurement network was expanded step by step. Since August 2011, data were available from all rooms in buildings O-1 and O-2. Since May 2012, data from all rooms characterised in *Table 1* were available.

Tab. 1 Characteristics of the buildings and rooms where the measurements were performed. Rooms with 'R' are located in residential buildings; rooms with 'O' are located in office buildings. Room H-1-1 is located in a hospital. Rooms O-1-1 to O-1-5 are located in one building of the Department of Geography, and rooms O-2-1 to O-2-5 are located in the second building. The ages of the buildings are categorised as "old" (built before 1960, built with bricks) and "new" (built after 2000, built with concrete). LCZ indicates the local climate zone according to Stewart and Oke (2012). The last column shows to which wall (interior or exterior wall) within a room the sensor was fixed.

Room	Age of building	LCZ	Use of room	Floor level	Aspect of the exterior wall	Wall with sensor
R-1-1	New	Compact midrise	Living room	1	NW+SW	Interior
R-2-1	Old	Compact midrise	Living room	3	SW	Exterior
R-3-1	Old	Compact midrise	Living room	4	SE	Interior
R-4-1	Old	Compact midrise	Living room	1	SW	Interior
H-1-1	Old	Open midrise	Patient room	3	SW	Interior
O-1-1	Old	Open midrise	Workshop	Ground	NE	Interior
O-1-2	Old	Open midrise	Storeroom	Ground	SW	Interior
O-1-3	Old	Open midrise	Seminar room	1	NE	Exterior
O-1-4	Old	Open midrise	Office room	3	NE	Interior
O-1-5	Old	Open midrise	Office room	3	SW	Exterior
O-2-1	New	Open midrise	Seminar room	Ground	SE+SW	Interior
O-2-2	New	Open midrise	Office room	2	NE+NW	Interior
O-2-3	New	Open midrise	Office room	2	SE+SW	Interior
O-2-4	New	Open midrise	Office room	4	NE+NW	Exterior
O-2-5	New	Open midrise	Office room	4	SE+SW	Interior
O-3-1	Old	Low midrise	Office room	1	SE	Exterior

Note: Due to a modernisation before the measurements, the building R-2 has a new building insulation.

Here, results are presented from the measurements until September 2012. Because the research focused on heat stress characterisation, only data from May until September were evaluated. Due to network errors, there were periods with missing data. Therefore, comparisons between the different rooms are only given if data availability for all rooms is higher than 80 %.

The UTCI values can be directly connected to categories of thermal stress. According to *Bröde* et al. (2012), values ranging from 9 °C to 26 °C are considered to represent conditions with no thermal stress, values between 26 °C and 32 °C suggest moderate heat stress and values between 32 °C and 38 °C indicate strong heat stress. The UTCI values outside of these categories did not occur during the measurements. Based on the minute averages of the UTCI values, frequencies of moderate or strong heat stress for a given period were calculated as the percentage of minutes with UTCI values matching the stated categories of thermal stress.

3. Results

3.1 Spatial distribution of thermal conditions

The results of the measurements and the calculated UTCI values are shown for the different buildings in *Table 2* for two periods in 2012. *Table 3* gives the same data for ten rooms in the two buildings of the Department of Geography of the Humboldt-Universität (O-1 and O-2), where a sufficient amount of data is available for the period from 1 August to 30 September 2011 and 1 May to 30 September 2012.

Except for buildings O-1 and O-2, where multiple rooms were included in the evaluation, only minor differences could be found for the various parameters, which will be presented in this section. The mean air temperature varied over a range of 2.2 K during the period from 1 May to 30 June 2012, hereafter referred to as period one, from 21.8 °C to 24.0 °C, and in a range of 2.4 K in the period from 1 May to 31 August 2012, hereafter referred to as period two. The air humidity differed by 10 % in period one and 9 % in period two. Because the humidity values are, in general, below or slightly above 50 %, which is the reference humidity for temperatures under 29 °C in the UTCI model (*Bröde* et al. 2012), the mean UTCI values are lower or equal to the air temperature values. The greatest difference of 0.8 K between mean temperature and mean UTCI values was observed in O-3. The calculation of the UTCI also reduces the differences in the mean thermal indoor environment between the rooms compared to the differences in the mean temperature. The mean UTCI shows differences of 1.6 K in period one and 1.9 K in period two. The differences of the maximum UTCI values between the various rooms are nearly twice as high as the differences of the mean UTCI. Interestingly, the highest UTCI values occurred not in O-3, which showed the highest mean UTCI values, but in H-1. Pronounced variation could be found in the mean daily amplitudes of the UTCI, covering a range from 1.0 to 3.6 K.

The values from the ten rooms in buildings O-1 and O-2 in *Table 2* show more variation compared to other buildings. They overlap the range of values from the other rooms, with only minor exceptions. These exceptions include the mean temperature in period one, where the lowest value was found in R-4. Generally, the air humid-

Tab. 2 The thermal environment in buildings. Mean air temperature, mean air humidity, mean UTCI, mean daily amplitude (Daily-Δ) of UTCI, maximum UTCI and data availability (DA) for the different buildings are shown. Mean values and standard deviations (sd) were calculated from the mean daily values. Because five rooms with measurement equipment are located in buildings O-1 and O-2, ranges for these five rooms are given. The two periods are shown with R-3 missing in the second period, due to low data availability in R-3 from July 2012 on.

	Building	Temperature (°C) mean ± sd	Humidity (%) mean ± sd	UTCI (°C) mean ± sd	UTCI Daily-Δ (K) mean ± sd	UTCI max (°C)	DA (%)
Period 1: 1 May to 30 June 2012	R-1	23.2 ± 0.7	47 ± 7	22.9 ± 1.0	2.1 ± 0.8	26.8	91
	R-2	22.2 ± 0.9	50 ± 7	22.0 ± 1.0	3.6 ± 1.3	25.9	91
	R-3	22.4 ± 1.4	46 ± 7	22.0 ± 1.4	1.7 ± 0.8	26.9	89
	R-4	21.8 ± 1.3	50 ± 6	21.6 ± 1.3	2.0 ± 1.1	26.3	95
	H-1	23.8 ± 1.2	41 ± 8	23.1 ± 1.4	2.6 ± 1.1	28.9	92
	O-1	21.9 – 24.3	37 – 42	21.3 – 23.6	0.5 – 2.0	23.1 – 28.6	> 93
	O-2	22.3 – 27.0	35 – 42	21.7 – 26.1	1.8 – 2.9	26.9 – 33.4	> 80
	O-3	24.0 ± 1.4	40 ± 3	23.2 ± 1.4	1.0 ± 0.4	26.4	92
Period 2: 1 May to 31 August 2012	R-1	23.8 ± 1.0	50 ± 7	23.6 ± 1.4	2.1 ± 0.7	28.0	84
	R-2	22.9 ± 1.3	53 ± 7	22.9 ± 1.6	3.6 ± 1.4	28.0	94
	R-4	22.5 ± 1.5	53 ± 7	22.5 ± 1.7	1.9 ± 1.0	27.3	91
	H-1	24.3 ± 1.4	44 ± 9	23.9 ± 1.7	2.6 ± 1.1	31.0	81
	O-1	22.5 – 25.1	41 – 48	22.2 – 24.6	0.5 – 1.7	24.7 – 30.2	> 96
	O-2	22.8 – 27.8	37 – 48	22.6 – 27.1	1.6 – 3.0	27.9 – 35.6	> 84
	O-3	24.9 ± 1.6	44 ± 4	24.4 ± 1.8	1.0 ± 0.4	29.5	96

Tab. 3 The thermal environment in the Department of Geography of Humboldt-Universität. Mean air temperature, mean air humidity, mean UTCI, mean daily amplitude (Daily-Δ) of UTCI, maximum UTCI and data availability (DA) for the ten rooms are shown. Mean values and standard deviations (sd) were calculated from the mean daily values.

Period	Room	Temperature (°C) mean ± sd	Humidity (%) mean ± sd	UTCI (°C) mean ± sd	UTCI Daily-Δ (K) mean ± sd	UTCI max (°C)	DA (%)
Period: 1 August to 30 September 2011 and 1 May 2012 to 30 September 2012	O-1-1	22.3 ± 0.9	51 ± 7	22.1 ± 1.1	0.6 ± 0.2	24.8	98
	O-1-2	23.1 ± 1.0	44 ± 4	22.5 ± 1.1	0.5 ± 0.2	25.1	97
	O-1-3	24.1 ± 1.4	46 ± 6	23.7 ± 1.5	0.9 ± 0.5	28.3	98
	O-1-4	24.4 ± 1.8	45 ± 6	23.9 ± 1.9	1.8 ± 0.9	29.5	99
	O-1-5	24.1 ± 2.0	44 ± 6	23.6 ± 2.1	1.4 ± 0.7	30.2	99
	O-2-1	22.8 ± 1.1	49 ± 10	22.6 ± 1.4	1.8 ± 0.8	28.3	88
	O-2-2	26.0 ± 2.3	42 ± 5	25.4 ± 2.3	2.7 ± 0.7	32.1	89
	O-2-3	26.8 ± 1.8	41 ± 6	26.2 ± 2.0	2.6 ± 1.2	33.9	99
	O-2-4	24.7 ± 2.3	46 ± 7	24.4 ± 2.3	2.1 ± 0.8	31.6	93
	O-2-5	27.7 ± 2.3	38 ± 5	27.0 ± 2.5	3.3 ± 1.3	35.6	88

ity is also lower in buildings O-1 and O2, especially compared to the rooms in the residential buildings. Another exception is the mean daily amplitude of the UTCI. R-2 showed the greatest variation of this parameter.

The data in *Table 3* give a deeper insight into the different thermal indoor environments of individual buildings. Within the two buildings, the greatest difference of 0.7 K between mean temperature and mean UTCI values was observed in room O-2-5. The rooms in building O-1 have lower mean temperatures, ranging from 22.3 °C to 24.4 °C, compared to the rooms in building O-2, where the mean temperatures vary from 22.8 °C to 27.7 °C. In general, the mean UTCI values, mean daily amplitudes of the UTCI and maximum UTCI values are also higher in building O-2, whereas the humidity tends to be higher in building O-1. As found for the data in *Table 2*, the mean UTCI values show a lower variation between the rooms compared to the mean temperature due to humidity levels near or below 50 %. The highest UTCI value was found in room O-2-5 on 20 August 2012, where a maximum of 35.6 °C was reached between 13:07 and 13:09 CET. Inside the two buildings, the temperature and the UTCI values tend to increase with increasing floor level. The highest vertical differences in rooms within one building, and with the same aspect of the exterior wall, was found between rooms O-2-1 and O-2-5, with a mean temperature difference of 4.9 K, a mean UTCI difference of 4.4 K and a difference of the maximum UTCI of 7.3 K.

The described differences in the mean and maximum UTCI values between buildings and within buildings O-1 and O-2 are also reflected in the distribution of indoor heat stress frequency. In period two, all rooms in buildings for which only one room was evaluated showed moderate heat stress, but no strong heat stress occurred in these rooms (*Fig. 2*). The lowest frequency of moderate heat stress was detected in R-2 (4 %), and the highest frequency occurred in O-3 (20 %). Greater variations were found in buildings O-1 and O-2. During period two, the range reached from rooms with no moderate heat stress to rooms with strong heat stress.

The detailed distribution of heat stress frequency for the ten rooms in the Department of Geography can be found in *Figure 3* for the period from 1 August to 30 September 2011 and 1 May to 30 September 2012. No heat stress occurred in the two rooms at the ground floor level in building O-1, and no rooms in this building showed strong heat stress. In building O-2, moderate heat stress was detected in all of the rooms, and strong heat stress occurred in three rooms. While strong heat stress only lasted seven minutes in room O-2-2, room O-2-5 experienced strong heat stress for almost 170 hours.

3.2 Temporal course of the UTCI parameters

The temporal courses of the minimum, mean and maximum UTCI differ considerably between different buildings and also between rooms in buildings O-1 and O-2.

Figure 4 shows the variation over time for four selected rooms (R-2-1, R-4-1, O-3-1 and H-1-1), which represent different room characteristics. In all four rooms, moderate heat stress was detected, and no strong heat stress occurred because the maximum UTCI was always below the threshold of 32 °C. While all four rooms experienced moderate heat stress with regard to the mean UTCI, the minimum UTCI was always in the regime of no thermal stress in the two rooms in residential buildings. Hence, no

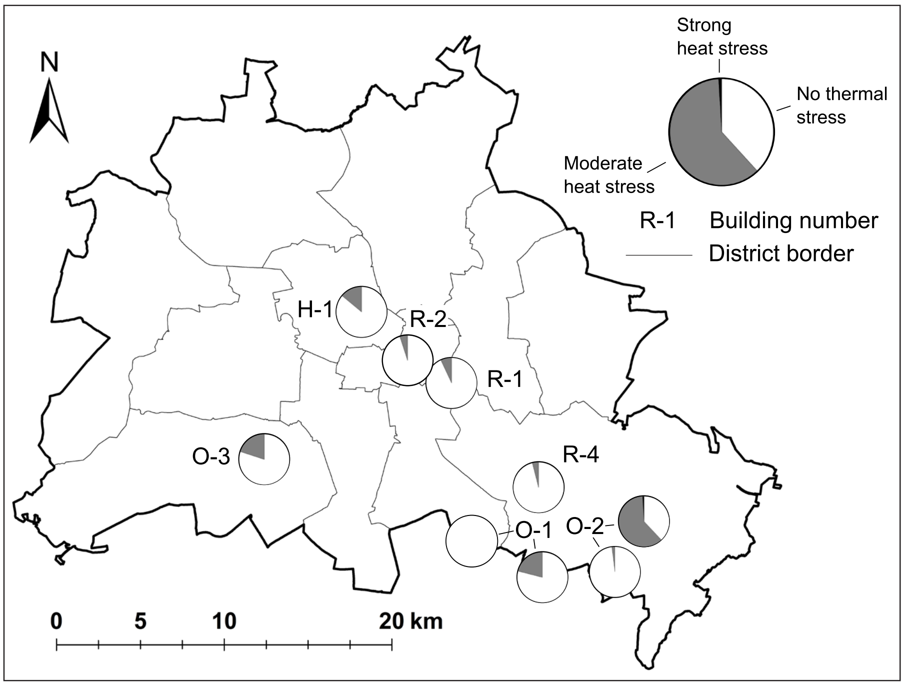

Fig. 2 The distribution of the indoor heat stress frequency in Berlin from 1 May to 31 August 2012 based on the UTCI values. For buildings O-1 and O-2 the range of distribution for the five rooms is given.

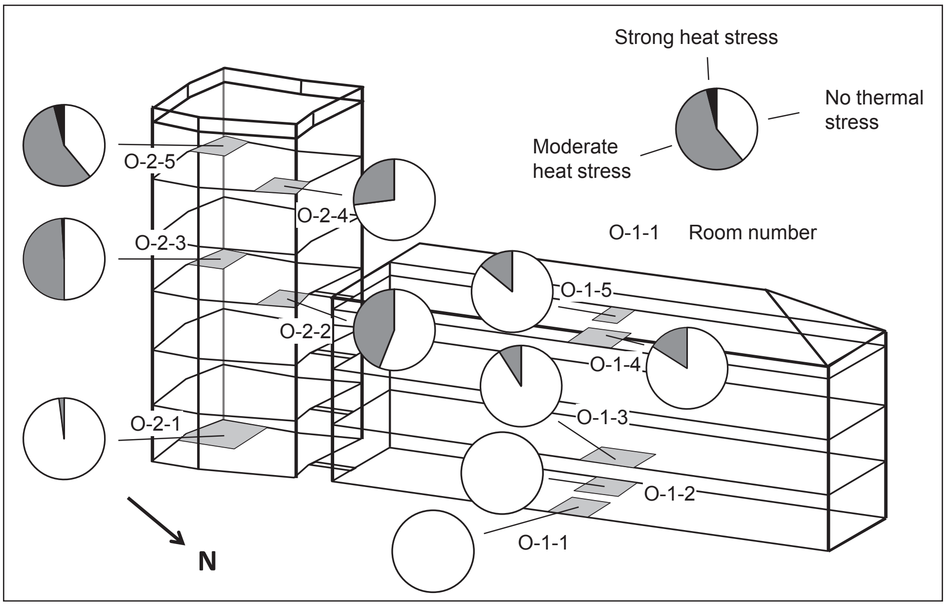

Fig. 3 The distribution of the indoor heat stress frequency from 1 August to 30 September 2011 and 1 May to 30 September 2012 in the two buildings of the Department of Geography of Humboldt-Universität based on the UTCI values

episodes of moderate heat stress occurred in these rooms. O-3-1 and H-1-1, however, experienced a daily minimum UTCI that exceeded 26 °C. There was no sufficient cooling during the night, so moderate heat stress lasted at least 24 hours.

Even more pronounced differences can be seen in *Figure 5*, where the course of the UTCI in room O-1-1 is compared to room O-5-2. In O-1-1, in which the lowest UTCI values of all of the rooms were measured, the daily fluctuation of the UTCI is very low and does not exceed 1.4 K. In contrast, the daily variation of the UTCI reached 6.5 K in room O-5-2. There were also long episodes of moderate heat stress in this room. Starting on 17 August 2012, a period of 21 days was observed in which the UTCI values were continuously at least within the moderate heat stress regime. Within this period, the frequency of strong heat stress was 15 % and the minimum UTCI peaked during one night at 32.0 °C, just above the threshold of strong heat stress. During the period shown in *Figure 5*, the maximum differences between these two rooms were 8.6 K for the daily minimum UTCI, 9.8 K for the daily mean UTCI and 12.2 K for the daily maximum UTCI. These UTCI differences corresponded to differences in temperature of 8.8 K, 9.7 K and 12.1 K, respectively. Nevertheless, during two nights in September 2012, the UTCI values in room O-5-2 fell below the UTCI values in room O-1-1.

Figure 6 gives an overview of four selected pairs of rooms, showing the main characteristics regarding the relation between the daily minimum, mean and maximum UTCI values that can be found by comparing different rooms. The thermal environment in rooms R-2-1 and R-4-1, as well in O-2-3 and O-2-5, shows a similar temporal behaviour, as indicated by an R^2 of up to 0.8. The rooms are similar with respect to the aspect of the exterior wall, the use of the room, the type of building and the local climate zone (see *Tab. 1*). If the combination of these factors varies considerably between two rooms, the variation of the daily UTCI values is much higher, even if the spatial distance between the rooms amounts only to a few tens of metres. O-1-1 and O-2-5 show different thermal behaviour, which was also discussed in the previous section and is emphasised by the R^2 values below 0.44 (*Fig. 6*), although these two rooms are only separated by approximately 50 m.

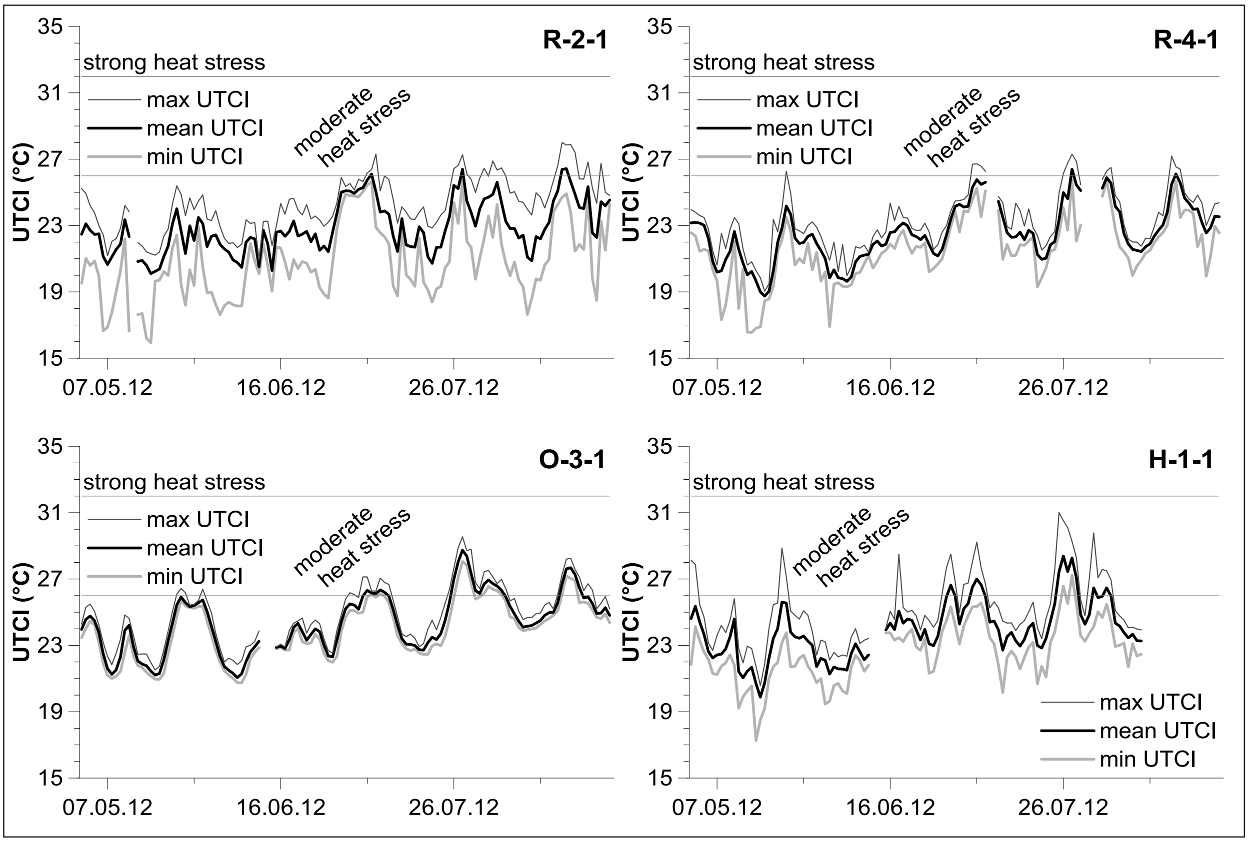

Fig. 4 The temporal course of the daily minimum, mean and maximum UTCI values in four rooms in different buildings from 1 May to 30 August 2012

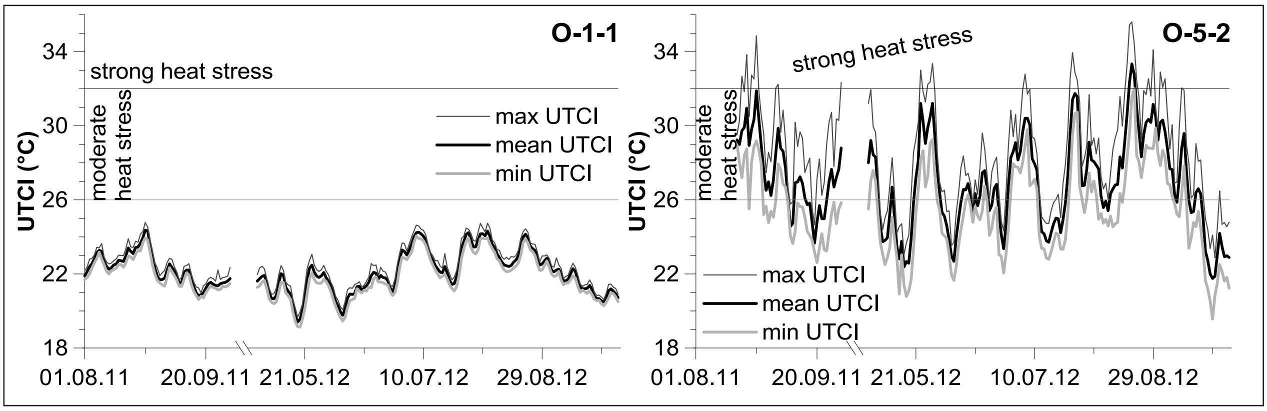

Fig. 5 The temporal course of the daily minimum, mean and maximum UTCI values in the two rooms in the Department of Geography of Humboldt-Universität from 1 August to 30 September 2011 and from 1 May to 30 September 2012

4. Discussion

Using the specified assumptions regarding air velocity, mean radiant temperature and metabolic heat production, it was possible to calculate the UTCI values from the measured air temperature and air humidity in indoor environments, thereby resulting in low differences between the air temperature and the UTCI values. But there are certain constraints that have to be considered. First, UTCI values will be overestimated using the reference conditions for indoor environments. The activity level of humans in indoor environments, e.g., while seating or sleeping, is mostly lower than 135 W/m^2. Assuming a resting level of 64 W/m^2, *Bröde* et al. (2013) calculated correction terms of up to 6 to 8 °C for indoor conditions. Especially during nighttime, this would lead to considerably lower heat stress as indicated by the UTCI values given in this study. Second, air velocity will typically be below 0.3 m/s in these environments. This will result in a higher heat stress than determined by the calculated UTCI values. However, if ventilation is used in hot conditions, air velocity may be higher than 0.3 m/s and, as a consequence, UTCI values would be overestimated with the used assumptions. Third, heating of indoor air is mainly governed by direct radiation incident on the exterior walls of the buildings during the daytime in the summer. This effect can be deduced from the pronounced variation of temperature and the subsequent UTCI values within the rooms of buildings O-1 and O-2, which are exposed to approximately the same outdoor air temperature. Therefore, rooms facing direct solar radiation may have a higher surface temperature on the inside walls compared to the indoor air temperature, which leads to a higher mean radiant temperature during the daytime, as indicated by the indoor air temperature. If the mean radiant temperature is set to the indoor air temperature in these situations, the UTCI will be underestimated. Up to now, there is no validated procedure to determine UTCI values under these indoor conditions differing from the reference conditions. If such a procedure will be available in future studies, the values given here may be re-evaluated. Nevertheless, the statements regarding spatial differences and temporal behaviour of thermal conditions will still be valid.

Because the relative humidity was typically below or slightly above 50 %, the UTCI values are, generally, lower than the air temperature. For the urban scale, *Fischer* et al. (2012) found an urban humidity deficit compared to rural surroundings, which could only partly compensate for the additional heat stress caused by the urban heat island.

The differences in the mean indoor air temperatures of the buildings where only one room was evaluated were below 2.4 K, corresponding to UTCI differences below 2 K. Even the maximum UTCI values showed differences below 4 K in these buildings, which are distributed over different districts of Berlin, ranging from the city centre to the outskirts. Rooms with comparable environments with respect to the factors influencing indoor thermal conditions, such as the characteristics of the building, show particularly minimal differences in the mean temperature and high correlations between the different UTCI parameters. In general, these differences are small compared to the expected differences in outdoor air temperatures. According to *Wienert* and *Kuttler* (2005), cities at the same latitude as Berlin, which is located at 52°N, show a maximum urban heat island intensity ranging from 2 to 12 K. *Scherer* et al. (2013) reported the strongest urban heat island intensities during summer nights in Berlin, up to 10 K. Simultaneously, rooms in the two neighbouring buildings, O-1 and O-2, showed a vari-

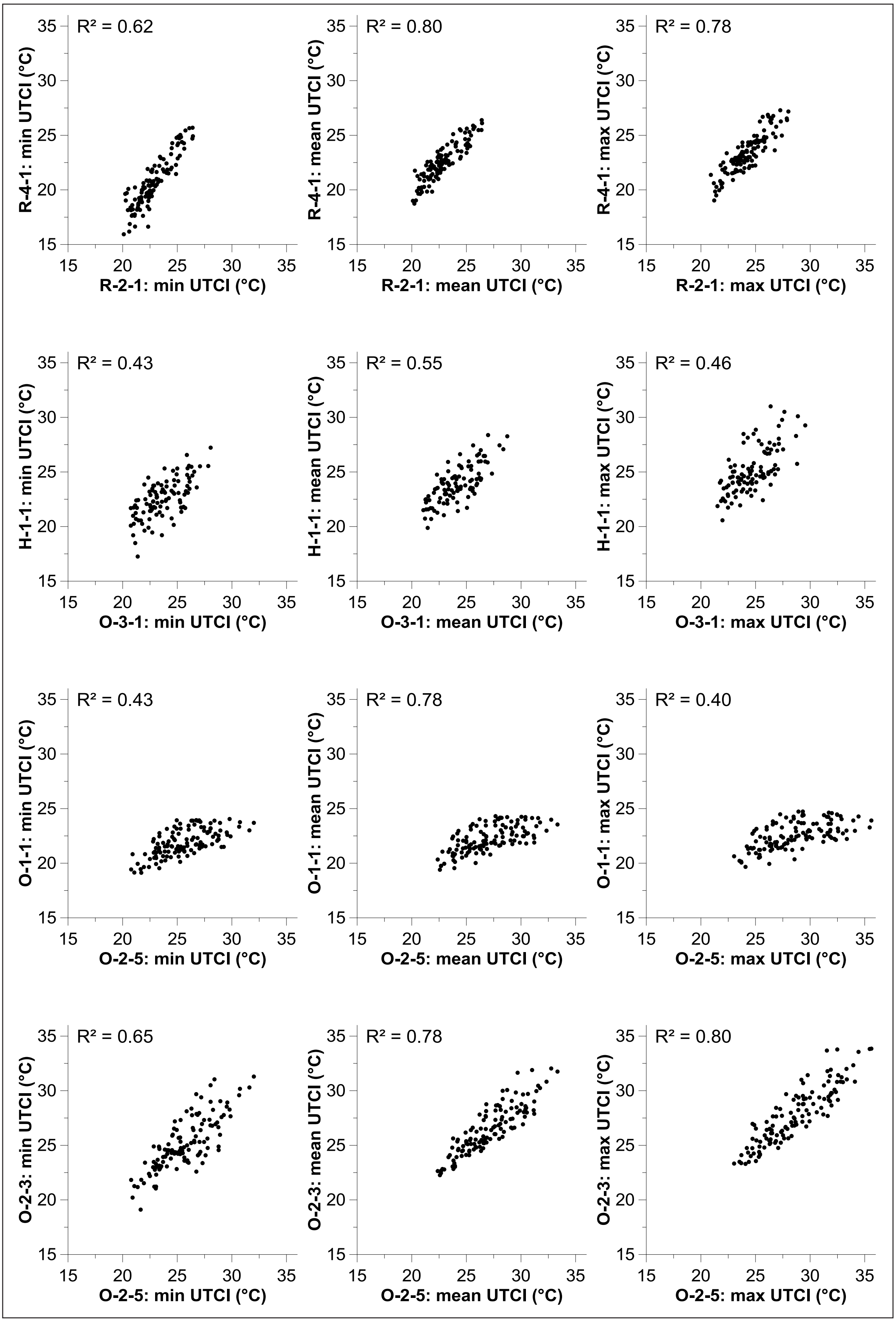

Fig. 6 Scatter plots of the daily minimum, mean and maximum UTCI values for the four selected pairs of rooms from 1 May to 30 August 2012

ation of both air temperature and UTCI above 12 K. With respect to temperature variation, these buildings can be regarded as miniature urban heat islands.

The results obtained from the measurements in buildings O-1 and O-2 provide information about the factors governing indoor thermal conditions. In addition to the outdoor atmospheric conditions, various factors influence the indoor environment. *Mirzaei* et al. (2012) successfully developed a model to predict the indoor temperature using building occupancy, building volume, building aspect ratio, location of the indoor temperature measurement, vegetation ratio and hour of day as input parameters, apart from different parameters describing the outdoor atmospheric conditions. The calculated indoor temperatures showed a large heterogeneity on an urban micro-scale, similar to what was found in this study.

Temperatures and UTCI values are lower in building O-1 compared to building O-2. This result can be explained by the differences with respect to the construction material. Because glass has a lower specific heat capacity compared to concrete or bricks, the walls of building O-1 have a higher heat capacity that acts as a thermal buffer. Therefore, the rooms in building O-1 are prevented from heating up into the range of strong heat stress, as observed in building O-2. Furthermore, building insulation attenuates heat transfer through walls and reduces warming of rooms during summer months. This might be the reason for the low frequency of moderate heat stress, which was detected in room R-2-1

In general, the temperature and the UTCI values increased with increasing floor level in buildings O-1 and O-2. For rooms with the same aspect, mean temperature differences amounted up to 4 K between the three floor levels. Comparable differences were described for a building in Freiburg during August 1997 (WHO 2004). This result reflects the influence of heating by absorbed solar radiation. The exterior walls of rooms on lower floor levels are shaded by trees or neighbouring buildings, whereas higher floor levels are exposed to direct solar radiation. The increased heating during the daytime is accompanied by increased long-wave emission during the night. The resulting cooling of the upper part of the buildings during the night, which is supported by higher wind velocities outdoors compared to the lower parts and could be observed by infrared thermography in 2012 (data are not shown here), is responsible for the lower differences of the minimum UTCI values between the rooms compared to the differences of the maximum UTCI. At the end of summer, the cooling is so effective that, occasionally, the minimum UTCI values in room O-1-1 are higher than in room O-2-5. In some rooms, the influence of occupancy on the thermal environment could be observed. Less-frequented rooms (O-1-1 and O-1-2) showed small daily variations. A continuously tilted window in room O-2-4 could be responsible for lower heat stress compared to room O-2-2.

5. Conclusions

The distribution of heat stress in indoor environments showed a small-scaled heterogeneity that was mainly governed by the characteristics of the buildings and their surroundings. A significant influence of the outdoor urban heat island could not be found because it is only one factor among several parameters that are responsible for the development of the indoor thermal environment. To isolate the effect of the urban heat island, more buildings must be included in the study.

As direct solar radiation is an important factor for the development of indoor heat stress during the daytime, the concept of low climate zones seems to be a useful tool to give the first hints of the indoor thermal conditions in buildings in different zones. For example, it can be assumed that there are characteristic differences between buildings in the compact midrise zone and buildings in the open midrise zone because the latter may be exposed to more intense solar radiation, leading to pronounced heating in the upper floor levels, accompanied by improved night-time cooling, as it was shown for buildings O-1 and O-2 in the discussion. A systematic investigation of these relations seems to be a promising approach for further studies, which should also include outdoor atmospheric conditions. Future research could also focus on the micro-scale distribution of air temperature inside the rooms by simultaneous measurements at different locations, especially in the middle of the room, to prove the representativeness of single measurements. In addition, an integration of measurements of the temperature of the walls in further studies should provide more accurate information about the mean radiant temperature.

The assessment of indoor heat stress must consider the nighttime conditions because they have a particular effect on recreation and sleep depth (WHO 2004).

From this perspective it is alarming that, in buildings without air conditioning, strong heat stress may occur throughout the night, assumed a rate of metabolic heat production of 135 W/m^2. Architects and city planners must be aware of the emergence of these unfavourable conditions for human health and include the appropriate countermeasures in their plans.

Note

[1] A summer day is defined by a maximum daily air temperature ≥ 25 °C, a hot day is defined by a maximum daily air temperature ≥ 30 °C.

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References

Almeida, S., E. Casimiro and *A. Analitis* 2013: Short-term effects of summer temperatures on mortality in Portugal: A time-series analysis. – Journal of Toxicology and Environmental Health, Part A: Current Issues **76** (7): 422-428

Amt für Statistik Berlin-Brandenburg (Hrsg.) 2012: Statistisches Jahrbuch 2012. – Berlin

Basagaña, X., C. Sartini, J. Barrera-Gómez, P. Dadvand, J. Cunillera, B. Ostro, J. Sunyer and *M. Medina-Ramón* 2011: Heat waves and cause-specific mortality at all ages. – Epidemiology **22** (6): 765-772

Bröde, P., D. Fiala, K. Błażejczyk, I. Holmér, G. Jendritzky, B. Kampmann, B. Tinz and *G. Havenith* 2012: Deriving the operational procedure for the Universal Thermal Climate Index (UTCI). – International Journal of Biometeorology **56** (3): 481-494

Bröde, P., D. Fiala and *B. Kampmann* 2013: Occupational thermal stress and the UniversalThermal Climate Index UTCI. – In: *Cotter, J.D., S.J. Lucas* and *T. Mündel* (eds.): Proceedings of the 15th international Conference on Environmental Ergonomics, Queenstown (NZ), February 11-15th, 2013: 206-209. – Online available at: http://www.lboro.ac.uk/microsites/lds/EEC/ICEE/textsearch/13proceedings/Environmental%20Ergonomics%20XV_Proceedings%20for%20Webpage.pdf, 30/12/2013

Endlicher, W. and *N. Lanfer* 2003: Meso- and micro-climatic aspects of Berlin's urban climate. – DIE ERDE **134** (3): 277-293

Fanger, P. O. and *J. Toftum* 2002: Extension of the PMV model to non-air-conditioned buildings in warm climates. – Energy and Buildings **34** (6): 533-536

Fernández-Raga, M., C. Tomás and *R. Fraile* 2010: Human mortality seasonality in Castile-León, Spain, between 1980 and 1998: the influence of temperature, pressure and humidity. – International Journal of Biometeorology **54** (4): 379-392

Fiala, D., G. Havenith, P. Bröde, B. Kampmann and *G. Jendritzky* 2012: UTCI-Fiala multi-node model of human heat transfer and temperature regulation. – International Journal of Biometeorology **56** (3): 429-441

Fischer, E.M., K.W. Oleson and *D.M. Lawrence* 2012: Contrasting urban and rural heat stress responses to climate change. – Geophysical Research Letters **39** (3)

Gabriel, K.M. and *W.R. Endlicher* 2011: Urban and rural mortality rates during heat waves in Berlin and Brandenburg, Germany. – Environmental Pollution **159** (8-9): 2044-2050

Hartz, D.A., A.J. Brazel and *J.S. Golden* 2013: A comparative climate analysis of heat- related emergency 911 dispatches: Chicago, Illinois and Phoenix, Arizona USA 2003 to 2006. – International Journal of Biometeorology **57** (5): 669-678

Havenith, G., D. Fiala, K. Błażejczyk, M. Richards, P. Bröde, I. Holmér, H. Rintamaki, Y. Benshabat and *G. Jendritzky* 2012: The UTCI-clothing model. – International Journal of Biometeorology **56** (3): 461-470

Hendl, M. 2002: Klima. – In: *Liedtke, H.* und *J. Marcinek* (Hrsg.): Physische Geographie Deutschlands. – Gotha, Stuttgart: 17-126

Jendritzky, G., R. de Dear and *G. Havenith* 2012: UTCI – Why another thermal index? – International Journal of Biometeorology **56** (3): 421-428

Kjellstrom, T. and *A.J. McMichael* 2013: Climate change threats to population health and well-being: the imperative of protective solutions that will last. – Global Health Action **6**: 20816

Kyselý, J. 2004: Mortality and displaced mortality during heat waves in the Czech Republic. – International Journal of Biometeorology **49** (2): 91-97

Lundgren, K., K. Kuklane, C.S. Gao and *I. Holmér* 2013: Effects of heat stress on working populations when facing climate change. – Industrial Health **51** (1): 3-15

Matzarakis, A. and *B. Amelung* 2008: Physiological equivalent temperature as indicator for impacts of climate change on thermal comfort of humans. – In: *Thomson, M.C., R. Garcia-*

Herrera and *M. Beniston* (eds.): Seasonal forecasts, climatic change and human health. Health and climate. – Advances in Global Change Research **30** – New York: 161-172

Matzarakis, A. and *C. Endler* 2010: Climate change and thermal bioclimate in cities: impacts and options for adaptation in Freiburg, Germany. – International Journal of Biometeorology **54** (4): 479-483

Mayer, H. and *P. Höppe* 1987: Thermal comfort of man in different urban environments. – Theoretical and Applied Climatology **38** (1): 43-49

Mendell, M. J. and *G. A. Heath* 2005: Do indoor pollutants and thermal conditions in schools influence student performance? A critical review of the literature. – Indoor Air **15** (1): 27-52

Michelozzi, P., G. Accetta, M. De Sario, D. D'Ippoliti, C. Marino, M. Baccini, A. Biggeri, H.R. Anderson, K. Katsouyanni, F. Ballester, L. Bisanti, E. Cadum, B. Forsberg, F. Forastiere, P.G. Goodman, A. Hojs, U. Kirchmayer, S. Medina, A. Paldy, C. Schindler, J. Sunyer, C.A. Perucci and *P.C. Grp* 2009: High temperature and hospitalizations for cardiovascular and respiratory causes in 12 European cities. – American Journal of Respiratory and Critical Care Medicine **179** (5): 383-389

Mirzaei, P.A., F. Haghighat, A.A. Nakhaie, A. Yagouti, M. Giguere, R. Keusseyan and *A. Coman* 2012: Indoor thermal condition in urban heat island – Development of a predictive tool. – Building and Environment **57**: 7-17

Monteiro, A., V. Carvalho, T. Oliveira and *C. Sousa* 2013: Excess mortality and morbidity during the July 2006 heat wave in Porto, Portugal. – International Journal of Biometeorology **57** (1): 155-167

Oke, T.R. 1982: The energetic basis of the urban heat-island. – Quarterly Journal of the Royal Meteorological Society **108** (455): 1-24

Osczevski, R. and *M. Bluestein* 2005: The new wind chill equivalent temperature chart. – Bulletin of the American Meteorological Society **86** (10): 1453-1458

Páldy, A., J. Bobvos, A. Vámos, R.S. Kovats and *S. Hajat* 2005: The effect of temperature and heat waves on daily mortality in Budapest, Hungary, 1970-2000. – In: *Kirch, W., B. Menne* and *R. Bertollini* (eds.): Extreme weather events and public health responses. – Berlin et al.: 99-107

Parsons, K.C. 2003: Human thermal environments: The effects of hot, moderate and cold environments on human health, comfort and performance. – 2nd edition. – London

Rocklöv, J., K. Ebi and *B. Forsberg* 2011: Mortality related to temperature and persistent extreme temperatures: a study of cause-specific and age-stratified mortality. – Occupational and Environmental Medicine **68** (7): 531-536

Scherer, D., D. Fenner and *F. Meier* 2013: Urban heat island anomalies in Berlin during the last decade. – Abstract book of ICUC8. – Dublin: 116

Senatsverwaltung für Stadtentwicklung und Umwelt 2011: Umweltatlas Berlin: 04.02 Langjähriges Mittel der Lufttemperatur 1961-1990. – Ausgabe 2011. – Online available at: http://www.stadtentwicklung.berlin.de/umwelt/umweltatlas/karten/pdf/04_02_2001.pdf

Statistisches Bundesamt 2013: Zensus 2011: Ausgewählte Ergebnisse. Tabellenband zur Pressekonferenz am 31. Mai 2013 in Berlin. – Wiesbaden. – Online available at: https://www.destatis.de/DE/PresseService/Presse/Pressekonferenzen/2013/Zensus2011/Pressebroschuere_zensus2011.pdf

Steadman, R.G. 1984: A universal scale of apparent temperature. – Journal of Climate and Applied Meteorology **23** (12): 1674-1687

Stewart, I.D. and *T.R. Oke* 2012: Local climate zones for urban temperature studies. – Bulletin of the American Meteorological Society **93** (12): 1879-1900

World Health Organization 2004: Heat-waves: Risks and responses. – Health and Global Environmental Change Series **2**. – Copenhagen. – Online available at: http://www.euro.who.int/__data/assets/pdf_file/0008/96965/E82629.pdf, 14/07/2013

Wienert, U. and *W. Kuttler* 2005: The dependence of the urban heat island intensity on latitude – a statistical approach. – Meteorologische Zeitschrift **14** (5): 677-686

Wyon, D.P. 2004: The effects of indoor air quality on performance and productivity. – Indoor Air **14** (7): 92-101