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Climatology

# Spatial variation of physiologically equivalent temperature in different Local Climate Zones of a large city during a hot spell

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**Abstract**

Global warming increases the risk of heat stress in Europe. Hence, heat stress must be considered as a health hazard for individuals working in outdoors and indoors conditions. Physiologically equivalent temperature (PET) is more related to the perceived temperature, but most of the current Local Climate Zone (LCZ) studies focus on measured temperature, instead of PET. Therefore, in this research, PET was applied to evaluate the thermal component of the outdoor microclimate for the first time in Berlin during a (1) hot spell, and (2) a normal period during July to August 2018. The aim of the present study is to explore the impacts of outdoor surroundings on human thermal comfort and its perception during the day and nighttime. Based on 32 micrometeorological stations located in different LCZs, the outdoor thermal sensation was investigated in order to find hourly thermal stress level conditions. Based on the mean hourly thermal sensation, the highest PET value was observed in, LCZ 4, "open high-rise" with 33.76 °C at 1400 CET, which represents a thermal stress level of "moderate heat stress". The LCZ 2 showed "slight heat stress", at the same time. High Sky View Factor (SVF) and relative humidity in "open high-rise" caused the highest PET. From the afternoon around 1800 CET to early morning 0600 CET, LCZ 2 is one thermal stress level warmer than all other existing LCZs in Berlin. During the hot spell, the hottest time period of the day was between 1600 CET to 1700 CET. In the morning from 0700 CET and midnight, the LCZ 2 was warmer than other local climate zones as the heat capacity of the buildings is high. Maximum hourly PET values illustrate that LCZ 4 was the warmest LCZ in which thermal sensation was 'very hot' between 0800 CET to 1700 CET. According to minimum hourly of PET, LCZ 4 was the coldest LCZs during the night and early in the morning.

**Keywords:** local climate zone (LCZ), hot spell, physiologically equivalent temperature (PET), microclimate, heat wave, Berlin

## 1 Introduction

Heat-waves have a detrimental effect on human health and can cause discomfort and heat stress, which can lead in extreme cases to death (Luber and McGeehin, 2008). Extreme high temperature cause heat-related disorders such as dehydration and sunstroke, and mortality due to cardiovascular and respiratory sicknesses (Curriero et al., 2002; Semenza et al., 1996). The extreme heat period in Europe (2003) and Russia (2010) led to about 70.000 and 55.000 deaths, respectively (Barriopedro et al., 2011; Robine et al., 2008). The high air temperature was responsible for 5 % of all deaths from 2001 to 2010 in Berlin (Scherer et al., 2014). Two intensive heat spell events during a 7-year period between 1999 to 2006 in Germany caused the highest rate of mortality in the densely built-up districts of Berlin (Gabriel and Endlicher, 2011). Urbanized zones compared to the natural or agricultural vicinity have different climate specifications which are called urban climate (Li et al., 2018; Oke, 2002).

The intense, frequent and long-lived extreme heat waves are projected to increase in the future (Christidis et al., 2015; Meehl and Tebaldi, 2004; Solomon et al., 2007), which can reduce the urban thermal comfort. Cities with their own landscape and microclimate also influence the perception of the physical well-being of their residents (Pearlmutter et al., 2014). Human thermal comfort conditions can be assessed through thermo-physiological indices in order to understand the effects of the thermal environment on humans. The thermal comfort condition occurs when the human body keeps the balance between the heat produced by the body and the lost heat without unnecessary activities (Höppe, 1999; Mayer, 1993). Some studies investigated the outdoor thermal comfort in different climate regions focused on heat stress (Eludoyin, 2014; Farajzadeh and Matzarakis, 2012; Holst and Mayer, 2011; Lee et al., 2013; Lee et al., 2016; Lee et al., 2014; Mayer et al., 2008; Nikolopoulou and Lykoudis, 2006; Spagnolo and De Dear, 2003; Urban et al., 2014). In the outdoor human thermal sensation, complex effects of air temperature, air humidity, short and long-wave radiation, and wind speed are considered. Therefore, an investigation of air temperature differences alone is not capable of demonstrating the outdoor thermal sensation of people (Höppe, 1999; Mayer, 1993).

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One of the most widely applied thermal indices is the PET (Höppe, 1999; Mayer and Höppe, 1987), which is the most commonly used index in outdoor thermal comfort studies (Johansson et al., 2014) and takes into account all basic thermoregulatory processes. It is the energy balance between human body absorption and surrounding emittance. PET takes in to account the following parameters: outdoor temperature, water vapor pressure, wind speed, and radiant energy (Höppe, 1999; Mayer, 1993).

Recently the Local Climate Zone (LCZ) concept was applied to compare the thermal response of environment with different built-up characteristics (e.g., Leconte et al., 2015; Skarbit et al., 2017; Stewart et al., 2014; Unger et al., 2014), and to analyze land form impacts on the microclimate scale (Middel et al., 2014). LCZs are defined as "*regions of uniform surface cover, structure, material, and human activity that span hundreds of meters to several kilometers in horizontal scale*" (Stewart et al., 2014).

Most researchers have studied urban temperature fields using the LCZ classification and fundamentally support the correspondence of LCZs with air temperature fields in the cities and their surroundings (Bechtel et al., 2015; Beck et al., 2018; Geletič and Lehnert, 2016; Lehnert et al., 2015)

A new application of the LCZ concept is outdoor human thermal comfort monitoring (Unger et al., 2014). Several investigations revealed that built-up area, like LCZ 1 ("compact high-rise") and LCZ 2 ("compact midrise") presents the highest PET. Areas with a proper vegetation distribution (dense and tall) have a lower PET value (Kovács and Németh, 2012; Milošević et al., 2016; Müller et al., 2014). Most of the thermal comfort studies based on LCZs confirmed that the LCZ classification scheme is one of the fundamental concepts for urban planners to design urban areas concerning the heat stress mitigation (e.g., Milošević et al., 2016; Müller et al., 2014; Unger et al., 2018).

In this study, we give an overview of outdoor human thermal sensation in different LCZs from urban and suburban micrometeorological stations during a hot spell from 17$^{th}$ of July until 9$^{th}$ of August (embedded hot spell) and a normal period from 1$^{st}$ until 16$^{th}$ July and 19$^{th}$ until 31$^{st}$ of August, 2018. We investigated hourly PET for the LCZ's of Berlin through the existing meteorological data network, to find out which hours are more stressful and which LCZs are more comfortable, where inhabitants could stay outside.

# 2 Data and methods

## 2.1 Study area

The study was conducted in Berlin, the capital city of Germany (52.52° N, 13.40° E). Berlin is located in eastern Germany and covers an area of about 892 km$^2$ (Fig. 1). Its population is approximately 3.6 million, and the topography is mainly flat and varies from 34 m to 115 m above sea level. Several lakes (5.9 ha), parks and forest areas (31.4 ha) characterize Berlin, while on the other hand 42 ha is covered by buildings (Dahlhausen et al., 2018). Based on Köppen's climate classification (Kottek et al., 2006), Berlin is located in the climate of Cfb (warm temperature (C), fully humid (f) and warm summer (b)). The annual mean summer air temperature from June to August (1961–1990) is 17.3 °C with 189 mm precipitation. The change of consecutive summer days is by two days, three days and nine days in 2018 with two, one and one day respectively, as well as the change of consecutive hot days by two days, three days, four days and six days with 0.5, 1.5, one and one respectively in comparison to the reference climate period from 1961–1990.

**Table 1:** Characteristics of LCZs in Berlin.

| LCZs | Definition | Area (%) | SV (Sky View Factor) | Number of Stations |
|---|---|---|---|---|
| LCZ 2 | Compact midrise | 7.9 | 0.25 | 3 |
| LCZ 4 | Open high-rise | 4.2 | 0.44 | 1 |
| LCZ 5 | Open midrise | 15.2 | – | – |
| LCZ 6 | Open low-rise | 29.4 | 0.35 | 8 |
| LCZ 8 | Large low-rise | 5.4 | 0.40 | 5 |
| LCZ A | Dense tree | 18.8 | 0.15 | 4 |
| LCZ B | Scattered tree | 6.4 | 0.27 | 4 |
| LCZ D | Low plants | 7.6 | 0.59 | 3 |
| LCZ G | Water | 5.1 | 0.57 | 5 |

## 2.2 LCZs classification

The LCZs classification is based on the measurable physical properties of the environment and the algorithm derives from the underlying physical parameters as defined by Stewart and Oke (2012).

Delineating the LCZs map in Berlin was carried out with the level 0 methodology proposed by the World Urban Database and Access Portal Tools (WUDAPT) (Bechtel et al., 2015) in this study. As the result, Berlin contains ten 'urban'/'built-up' and seven natural LCZs (Fig. 1). Table 1 shows the percentage of LCZs, SFV and the number of microclimate station. The largest areas are related to "open low-rise" (LCZ 6, 29.4 %) and "dense trees" (LCZ A, 18.8 %).

## 2.3 Meteorological data

The network of 33 micrometeorological stations, which measures air temperature and humidity at a height of 2 m (specified accuracy by manufacturer ±0.1 K in the range (−40 to +60 °C) were used maintained by the Meteorological Institute of the Freie Universität Berlin (Appendix A), which was a part of the project 'Urban climate under Change (Scherer et al., 2019a; 2019b). The number of stations in each LCZ is given in Table 1. Measurements are taken from 5-min momentum measures to

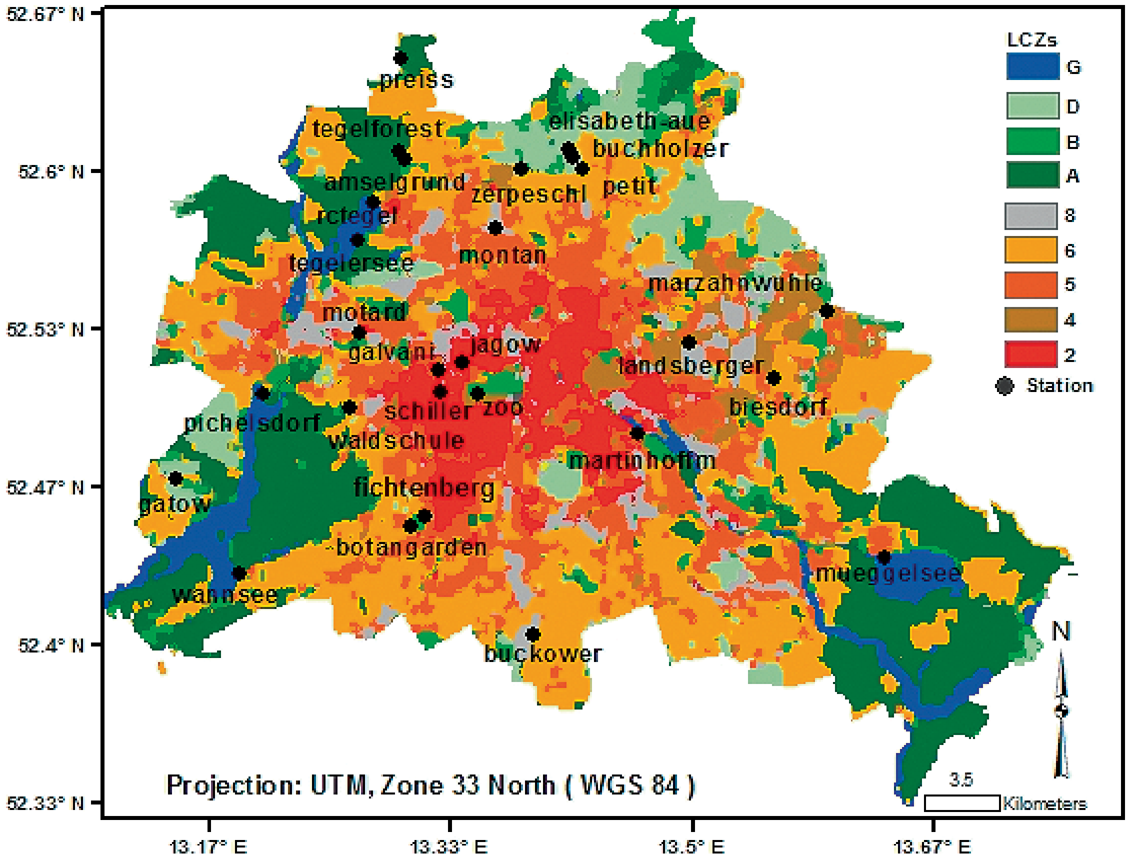


**Figure 1:** Local climate zone (LCZ) map of Berlin, Germany and locations of the micrometeorological stations (black symbols).

calculate 30-min average input data for PET calculation. The global radiation and wind speed data measured in a height of 34 m were taken from the station Fichtenberg (52.45° N, 13.31° E) located in LCZ 6 which presents the unshaded condition.

## 2.4 Selected period

The selected period was from 1st of July to 31st of August 2018 with an embedded hot spell from 17th of July to 8th of August 2018. The mean maximum air temperature in July reached 27.1 °C (+4 °C) and August 27.2 °C (+4.4 °C). The sunshine duration reached 342.8 h (+157 %) in July, and 284.4 h in August (+135 %). The amount of precipitation was 70.5 mm (+17.4 mm) and 4.8 mm (−60.5 mm) of the climate period from 1961 until 1990. The year 2018 was an extreme year with 28 hot days and 86 summer days (Fig. 2). During the last 37 years from 1981 to 2018, the absolute maximum air temperature varies between 26.1 °C (2000) to 37.9 °C (2015). The maximum air temperature in 2018 was 5 K higher than the average value of 1981 to 2017. Cubasch and Kadow (2011) published, that the temperature will increase by about 3.0–3.5 °C by the end of this century in Berlin-Brandenburg, based on the IPCC scenario A1B.

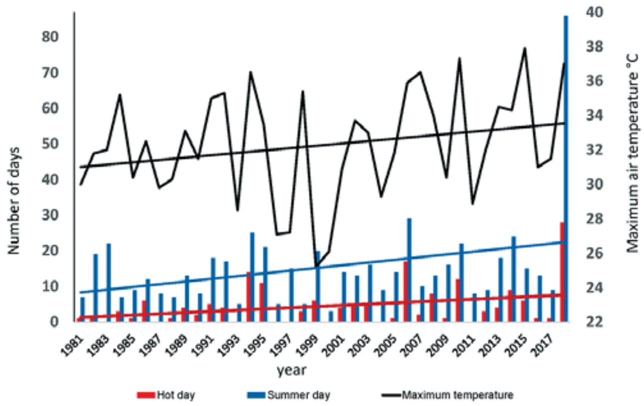


**Figure 2:** Summer days (maximum air temperature ≥20 °C, blue bars), and hot days (maximum air temperature ≥30 °C, red bars) for the time period 1981–2018 at the WMO-10381 station 'botanical garden'. Black line: maximum air temperature with a trend of 0.068 K/yr from 1981 to 2018.

## 2.5 The calculation of PET

PET values were computed through the RayMan software package (Lee et al., 2016; Matzarakis et al., 2010). Table 2 shows the PET classification, which is relevant for our analysis of the different LCZs for Berlin. Since the goal was to determine the thermal comfort conditions of the local scale, air temperature and humid-

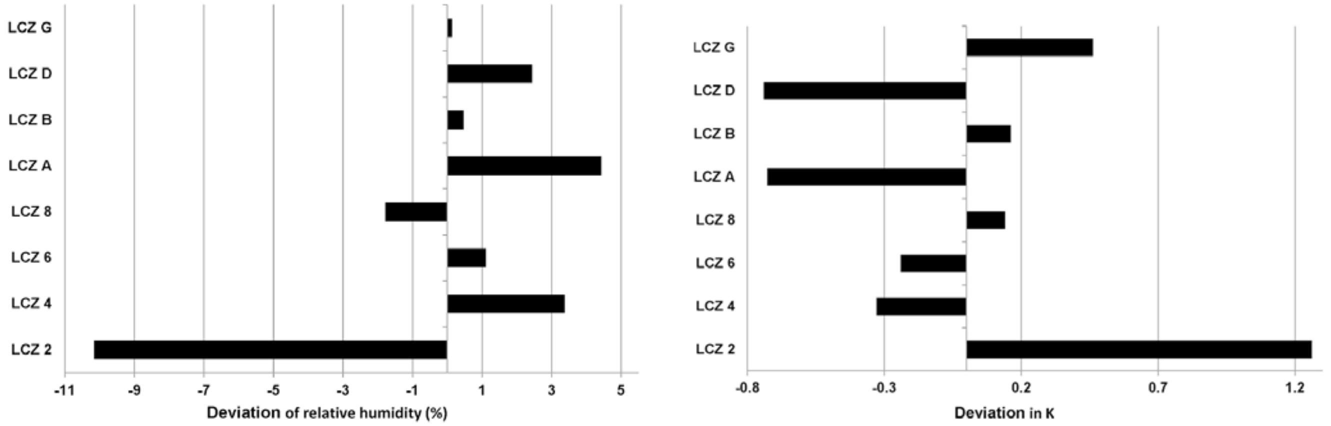


**Figure 3:** Deviation of the mean air temperature (21.3 °C) (right) and mean relative humidity (left) (60.6 %) from July to August 2018 for each LCZ.

**Table 2:** Thermal sensation and its corresponding stress level of PET in °C, (Matzarakis and Mayer, 1996).

| Thermal stress level | Human sensation | PET in °C |
|---|---|---|
| Extreme cold stress | Very cold | <4.0 |
| Strong cold stress | Cold | 4.1–8.0 |
| Moderate cold stress | Cool | 8.1–13.0 |
| Slight cold stress | Slightly cool | 13.1–18.0 |
| No thermal stress | Comfortable | 18.1–23.0 |
| Slight heat stress | Slightly warm | 23.1–29.0 |
| Moderate heat stress | Warm | 29.1–35.0 |
| Strong heat stress | Hot | 35.1–41.0 |
| | Very hot | >41.0 |

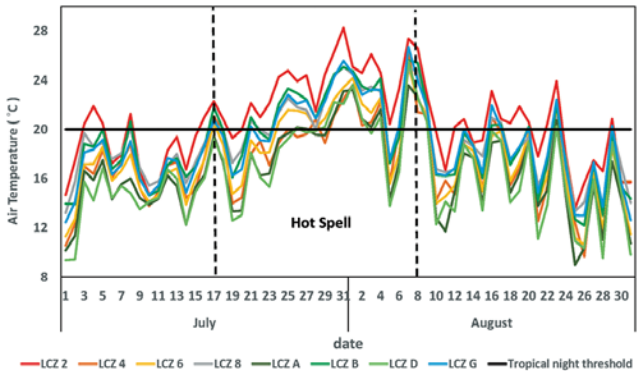


**Figure 4:** Minimum air temperature of each LCZ from 1st of July until 31st of August 2018 with the corresponding tropical night threshold line at 20 °C and the embedded hot spell from 17th of July to 9th of August.

ity data from each station presents the local scale and its corresponding LCZ.

Fisheye photos were selected from each station and PET was calculated as a mean value of the station in the corresponding LCZ. Global radiation and wind speed directly measured on site are not suitable for LCZ scale studies (Unger et al., 2018). They are highly affected by the micro-scale surroundings in order to avoid the affection of surrounding, therefore we use wind speed and global radiation data from unshaded station Fichtenberg. The corresponding wind speed data was reduced through logarithmic profile up to 2 m. The fraction of the visible sky on a hemisphere centered over the analyzed location was calculated with fisheye photos from each station, therefore the incoming radiation is more or less realistic for each station. The corresponding SVF (Table 1) of our station is similar to Stewart and Oke (2012) method.

# 3 Results and discussion

## 3.1 LCZ's air temperature and relative humidity distribution

The deviation of the corresponding temperature and relative humidity from mean value in the LCZs from July to August 2018 are displayed in Fig. 3. The "compact midrise" (LCZ 2) has the greatest air temperature deviation (+1.3 K) from the mean value (21.3 °C), which is similar in the Unger et al. (2014) research. The relative humidity of LCZ 2 has the greatest negative deviation (−10 %) from the mean value (60 %) due to the sealed surface. The LCZ G ("water"), is warmer (+0.5 K), due to the water temperature. The coolest and wettest LCZs are LCZ A ("dense trees ") and LCZ D ("low plant") respectively of the evapotranspiration.

## 3.2 Hot spell and normal period

For human well-being, it is important that the body cools down during the night, but during tropical nights where the air temperature does not fall below 20.0 °C it is difficult and can increase mortality rates. The minimum temperature from 1st of July to 30th of August varies between 10 °C to 28 °C from the LCZ 2 to the LCZ A (Fig. 4), but from 17th of July to 9th of August the air temperature was higher than 20 °C. Therefore, this period is considered as a hot spell and the rest of the period is considered as a normal period. The absolute

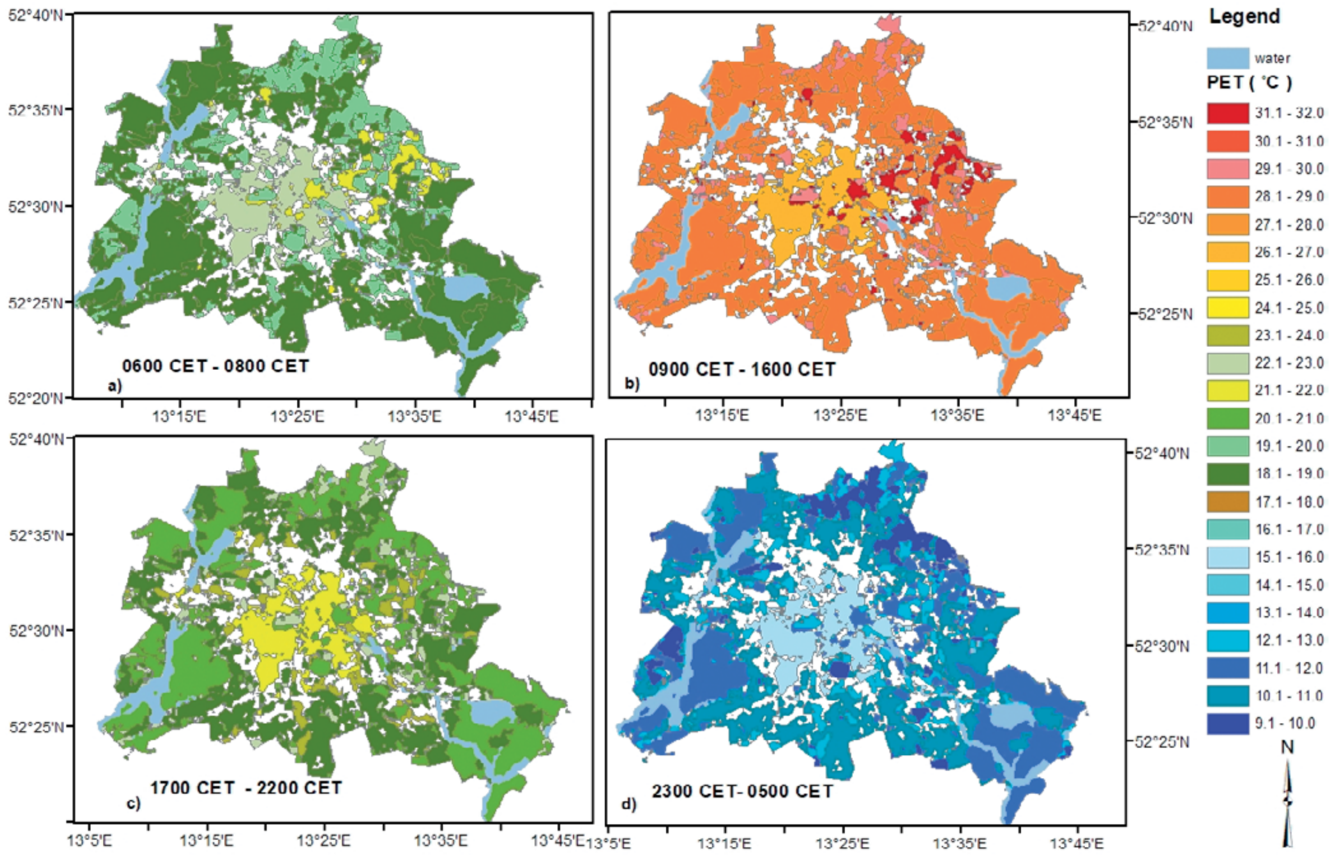


**Figure 5:** PET (°C) for the hot spell (17 July 2018 to 09 August 2018) for Berlin, a) 0600 CET–0800 CET b) 0900 CET–1600 CET c) 1700 CET–2200 CET d) 2300 CET–0500 CET.

daily minimum temperature reached 12.6 °C in suburban areas. LCZ D "low plants", "scattered trees" (LCZ B) and "dense trees" (LCZ A) show the lowest temperature due to more evaporation and less sensible heat. The highest and the lowest numbers of consequence tropical nights were observed in LCZ 2 (19 days) and LCZ D (5 days) respectively. Six consequence tropical nights in LCZ 4, A and 12 consequence tropical nights in LCZ 6, 8, B and G were observed

## 3.3 Mean hourly thermal sensation by LCZs during hot spell

As Fig. 5 demonstrated the spatial PET for the city, the hot spell divided in four time periods concerning the heat stress. Between the rush hour time from 0600 CET to 0800 CET, the daytime from 0900 CET to 1600 CET, the afternoon/evening time from 1700 CET to 2200 CET, and nighttime from 2300 CET to 0500 CET. At the afternoon/evening time, when inhabitants spend the recreation time outside, the highest PET for the whole city is reached in the (LCZ 2, which relate to human sensation of "slightly warm". In contrary, from 0600 CET to 0800 CET, when the minimum air temperature reached, the human sensation according to Matzarakis and Mayer, 1996 research is "comfortable" in LCZ 2, which is two-stress levels warmer than nighttime.

During daytime when inhabitants are outside, the LCZ 2 and the vegetated LCZ A show "slightly warm", but the open high-rise LCZ is one stress level warmer. Two reasons affect this human sensation, the relative humidity (Fig. 3), and the SVF (Table 1); the SVF is higher in LCZ 4, while LCZ 2 is the drier. However, the results show that a lower SVF where the station is much more shadowed and lower relative humidity during daytime causes a lower PET, during night it is inverted.

## 3.4 Thermal sensation variations of LCZs in the normal period

The daily variation of human thermal sensation during the normal period from 1st until 16th of July, and from 9th until 31st of August are shown through the minimum, mean and maximum human thermal sensation (Table 3a, b, c). The minimum hourly thermal sensation (Table 3a) show that the open high-rise LCZ and the vegetated LCZ D was the coldest in the night and early in the morning. According to the mean hourly thermal sensation (Table 3b) a 24-h day can almost split in two parts: between 0900 CET to 1800 CET which nearly all LCZs were "slightly warm", and at the nighttime from 2300 CET to 0600 CET with a "cool" human sensation. LCZ 2 was warmer than others in the morning and late

**Table 3:** a) Minimum, b) mean and c) maximum hourly human thermal sensation during the normal period

a)

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 0100 | Cl | VC | Co | Co | Co | Co | VC | Co |
| 0200 | Cl | VC | Co | Co | Co | Co | VC | Co |
| 0300 | Cl | VC | VC | Co | Co | Co | VC | VC |
| 0400 | Co | VC | VC | Co | VC | Co | VC | VC |
| 0500 | Cl | VC | VC | Co | Co | Co | VC | VC |
| 0600 | Cl | Co | Co | Co | Co | Co | VC | Co |
| 0700 | Cl | Cl | Co | Co | Co | Co | Co | Cl |
| 0800 | Cl | Cl | Cl | Cl | Cl | Cl | Cl | Cl |
| 0900 | Scl | Cl | Cl | Scl | Cl | Cl | Cl | Cl |
| 1000 | Scl | Cl | Cl | Cl | Cl | Cl | Cl | Cl |
| 1100 | Scl | Scl | Cl | Cl | Cl | Cl | Cl | Scl |
| 1200 | Scl | Cl | Cl | Scl | Scl | Cl | Cl | Scl |
| 1300 | Scl | Cl | Cl | Scl | Scl | Scl | Cl | Scl |
| 1400 | Scl | Scl | Cl | Scl | Scl | Scl | Scl | Scl |
| 1500 | Scl | Cl | Cl | Scl | Scl | Cl | Scl | Scl |
| 1600 | Scl | Cl | Scl | Scl | Scl | Scl | Scl | Scl |
| 1700 | Scl | Cl | Cl | Scl | Scl | Scl | Scl | Cl |
| 1800 | Cl | Cl | Cl | Scl | Cl | Scl | Cl | Cl |
| 1900 | Cl | Cl | Cl | Cl | Cl | Cl | Cl | Cl |
| 2000 | Cl | Co | Co | Cl | Cl | Cl | Co | Cl |
| 2100 | Cl | Co | Co | Cl | Co | Co | Co | Co |
| 2200 | Cl | Co | Co | Cl | Co | Co | VC | Co |
| 2300 | Cl | VC | VC | Co | Co | Co | VC | Co |

b)

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 0100 | Scl | Cl | Cl | Cl | Cl | Cl | Cl | Cl |
| 0200 | Scl | Cl | Cl | Cl | Cl | Cl | Cl | Cl |
| 0300 | Scl | Cl | Cl | Cl | Cl | Cl | Co | Cl |
| 0400 | Scl | Cl | Cl | Cl | Cl | Cl | Co | Cl |
| 0500 | Scl | Cl | Cl | Cl | Cl | Cl | Co | Cl |
| 0600 | Scl | Cl | Cl | Cl | Cl | Cl | Cl | Cl |
| 0700 | Cm | Scl | Scl | Scl | Scl | Scl | Scl | Cl |
| 0800 | SW | SW | Cm | Cm | Cm | Cm | Cm | SW |
| 0900 | SW | W | SW | SW | SW | SW | SW | W |
| 1000 | SW | SW | SW | SW | SW | SW | SW | SW |
| 1100 | Cm | SW | SW | Cm | SW | SW | SW | SW |
| 1200 | SW | SW | SW | SW | SW | SW | SW | SW |
| 1300 | SW | W | SW | SW | SW | SW | SW | SW |
| 1400 | Cm | W | SW | SW | SW | SW | SW | SW |
| 1500 | Cm | SW | SW | SW | SW | SW | SW | SW |
| 1600 | SW | W | SW | W | SW | SW | SW | SW |
| 1700 | SW | SW | SW | W | SW | W | SW | SW |
| 1800 | Cm | SW | Cm | SW | SW | SW | SW | SW |
| 1900 | Cm | Cm | Scl | Cm | Cm | Cm | Cm | Cm |
| 2000 | Scl | Scl | Scl | Scl | Scl | Scl | Scl | Scl |
| 2100 | Scl | Scl | Cl | Scl | Scl | Scl | Cl | Scl |
| 2200 | Scl | Cl | Cl | Scl | Cl | Scl | Cl | Cl |
| 2300 | Scl | Cl | Cl | Cl | Cl | Cl | Cl | Cl |

c)

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 0100 | Cm | Scl | Scl | Cm | Scl | Cm | Scl | Cm |
| 0200 | Cm | Scl | Scl | Cm | Scl | Cm | Scl | Scl |
| 0300 | Cm | Scl | Scl | Scl | Scl | Cm | Scl | Scl |
| 0400 | Cm | Scl | Scl | Scl | Scl | Scl | Scl | Scl |
| 0500 | Cm | Scl | Scl | Scl | Scl | Scl | Scl | Scl |
| 0600 | SW | Cm | Cm | Scl | Cm | Cm | Scl | SW |
| 0700 | H | H | W | W | W | W | W | H |
| 0800 | H | VH | H | VH | VH | VH | VH | VH |
| 0900 | VH | VH | VH | VH | VH | VH | VH | VH |
| 1000 | VH | VH | VH | H | VH | VH | VH | VH |
| 1100 | H | VH | VH | H | H | H | H | H |
| 1200 | H | VH | H | H | H | VH | H | VH |
| 1300 | VH | VH | H | H | H | H | H | VH |
| 1400 | H | VH | H | H | H | VH | H | H |
| 1500 | H | VH | H | VH | H | VH | H | H |
| 1600 | H | VH | H | VH | VH | VH | H | H |
| 1700 | W | VH | H | VH | VH | VH | H | VH |
| 1800 | W | H | W | VH | H | H | H | H |
| 1900 | SW | W | SW | H | W | W | W | W |
| 2000 | SW | SW | Cm | SW | SW | SW | SW | SW |
| 2100 | SW | SW | Cm | SW | SW | SW | SW | Cm |
| 2200 | Cm | Cm | Scl | Cm | Cm | Cm | Cm | Cm |
| 2300 | Cm | Scl | Scl | Cm | Scl | Cm | Scl | Scl |

VC : Very cold Co : Cold Scl : Slightly cool Cl : Cool Cm : Comfortable SW : Slightly warm W : Warm H : High VH: Very hot

at night. The maximum hourly thermal sensation (Table 3c) is also divided in two categories: the night time from 2200 CET to 0500 CET which varies from "comfortable" (LCZ 2) to "slightly warm" (LCZ 4, 6, A, D and G) and the daytime from 0800 CET to 1800 CET with the warmest zone of "very hot "in LCZ 4, while for the LCZ 2 a human sensation of "hot" was calculated. Summarizing during the normal period the human sensation in the different LCZ varies by 24-h day only by one corresponding stress level and the thermal sensation is clearly separated between day time and night time.

## 3.5 Thermal sensation variations of LCZs during the hot spell

According to the frequencies of the thermal sensation categories at each LCZ during the hot spell (Table 4), LCZ 2 was the warmest zone between 2200 CET and 0500 CET, which varied by 61.1 % to 73.9 % based on the human sensation "comfortable", while all other existing LCZs showed a "slightly cool" sensation with a frequency between 36.2 % to 69.1 %. From 1000 CET to 1500 CET, the highest percentage of human thermal sensation "very hot" was observed in LCZ 4 (~30 %). From 1600 CET to 1800 CET, LCZ 2 was "warm" 52.9 % of the time, while LCZs 4, 6, A, B, G, D were in a "hot" human sensation range of ~40 %. From 1900 CET to 2100 CET, the human sensations vary between "slightly warm" and "comfortable ", where the LCZ 6 shows the lowest frequency. These results show that in the morning (0700–0900 CET) and night (2200–0000 CET), the LCZ 2 is the hottest LCZ, since the heat capacity of the buildings is high; they emit the heat which they receive during the day.

Similar to the normal period, minimum, mean and maximum human thermal sensation during the hot spell was analyzed (Table 5a, b, c). During the minimum human thermal sensation (Table 5a) there is only at night time from 2300 to 0500 CET a clear differentiation of the thermal sensation from "cool" to "slightly cool" (LCZ 2). During daytime the thermal sensation change from "slightly cool" to "comfortable", only between 1600 CET to 1700 CET the LCZ large low-rise, dense trees and water dropped to a higher thermal sensation of "warm" and therefore the hottest time of the day. Based on mean 24-h day thermal sensation (Table 5b), open high-rise and the "water" LCZ were "hot" on daytime between 1200 CET to 1700 CET, while all other LCZ record a thermal sensation of "warm". No heat stress was observed from 1900 CET to 0700 CET in all LCZs and thermal sensation varied from "cool" to "comfortable". Maximum 24-h thermal sensation (Table 5c) demonstrate "very hot" in LCZs 4, B, D and G between 0900 CET to 1700 CET. Actually, from 0800 CET to 1900 CET, there is heat stress in all LCZs, since thermal sensations were "hot" and "very hot", but the "very hot" category was more frequent than "hot". Summarizing during the hot spell the human sensation in the different LCZ varies by 24-h day by four corresponding stress level "very hot"/"hot" on day time to "comfortable/"slightly warm "at night.

# 4 Conclusion

This study presents the human thermal comfort conditions in different LCZs during the hot spell time in summer 2018 in five built-up and four land covered areas of Berlin, Germany. Hourly PET and its corresponding human thermal sensation were calculated with the RayMan software based on 31 in-situ temperature/humidity measurements together with fisheye photos representative for each LCZ. The results of our study showed higher PET in the densely built-up areas in the evening and early in the morning which is in line with Fenner et al. (2014). The highest human sensation hours lasted from 2100 CET to 0800 CET during the hot spell when the classifications were "slightly

**Table 4:** Frequencies (%) of the thermal sensation classes of the LCZs during the hot spell (17 July to 9 August 2018).
Co: "Cold", Scl: Slightly Cold", Cl: Cool, Cm: Comfortable, SW: Slightly Warm, W: "Warm", H: "Hot", VH: "Very Hot"

| Time(CET) | PET Class | LCZ 2 | LCZ 4 | LCZ 6 | LCZ 8 | LCZ A | LCZ B | LCZ D | LCZ G |
|---|---|---|---|---|---|---|---|---|---|
| 0100–0300 | Cm | 70.6 | 1.5 | 0.0 | 11.8 | 4.4 | 17.9 | 3.0 | 11.9 |
| | Scl | 29.4 | 56.7 | 48.5 | 69.1 | 61.8 | 59.7 | 40.3 | 65.7 |
| | Cl | 0.0 | 37.3 | 45.6 | 19.1 | 33.8 | 22.4 | 43.3 | 22.4 |
| | Co | 0.0 | 4.5 | 5.9 | 0.0 | 0.0 | 0.0 | 13.4 | 0.0 |
| 0400–0600 | SW | 5.6 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| | Cm | 61.1 | 4.4 | 1.5 | 4.3 | 4.4 | 5.9 | 1.4 | 20.3 |
| | Scl | 31.9 | 60.3 | 47.1 | 66.7 | 55.9 | 69.1 | 39.1 | 59.4 |
| | Cl | 1.4 | 29.4 | 44.1 | 29.0 | 36.8 | 25.0 | 50.7 | 18.8 |
| | Co | 0.0 | 5.9 | 7.4 | 0.0 | 2.9 | 0.0 | 8.7 | 1.4 |
| 0700–0900 | VH | 3.0 | 14.5 | 2.9 | 4.3 | 3.0 | 5.9 | 8.8 | 16.2 |
| | H | 13.4 | 18.8 | 13.2 | 13.0 | 13.4 | 16.2 | 14.7 | 19.1 |
| | W | 35.8 | 24.6 | 22.1 | 21.7 | 23.9 | 20.6 | 17.6 | 29.4 |
| | SW | 22.4 | 17.4 | 25.0 | 24.6 | 25.4 | 26.5 | 27.9 | 20.6 |
| | Cm | 23.9 | 23.2 | 23.5 | 27.5 | 25.4 | 23.5 | 19.1 | 13.2 |
| | Scl | 1.5 | 1.4 | 13.2 | 8.7 | 9.0 | 7.4 | 11.8 | 1.5 |
| 1000–1200 | VH | 1.5 | 30.4 | 22.1 | 1.4 | 6.0 | 29.0 | 8.7 | 17.6 |
| | H | 25.0 | 15.9 | 30.9 | 10.1 | 31.3 | 34.8 | 26.1 | 30.9 |
| | W | 33.8 | 27.5 | 27.9 | 50.7 | 40.3 | 14.5 | 37.7 | 36.8 |
| | SW | 32.4 | 17.4 | 13.2 | 26.1 | 17.9 | 14.5 | 18.8 | 10.3 |
| | Cm | 7.4 | 4.3 | 1.5 | 10.1 | 3.0 | 5.8 | 7.2 | 4.4 |
| | Scl | 0.0 | 4.3 | 4.4 | 1.4 | 1.5 | 1.4 | 1.4 | 0.0 |
| 1300–1500 | VH | 3.0 | 30.4 | 10.1 | 8.7 | 10.1 | 17.4 | 11.8 | 20.3 |
| | H | 23.9 | 21.7 | 30.4 | 29.0 | 29.0 | 26.1 | 33.8 | 31.9 |
| | W | 37.3 | 27.5 | 27.5 | 37.7 | 34.8 | 31.9 | 30.9 | 34.8 |
| | SW | 29.9 | 13.0 | 24.6 | 20.3 | 21.7 | 20.3 | 19.1 | 11.6 |
| | Cm | 6.0 | 7.2 | 7.2 | 4.3 | 4.3 | 4.3 | 4.4 | 1.4 |
| 1600–1800 | VH | 0.0 | 17.4 | 5.8 | 36.2 | 19.7 | 36.4 | 11.6 | 19.1 |
| | H | 16.2 | 34.8 | 27.5 | 43.5 | 40.9 | 36.4 | 40.6 | 41.2 |
| | W | 52.9 | 27.5 | 44.9 | 17.4 | 31.8 | 22.7 | 40.6 | 32.4 |
| | SW | 29.4 | 17.4 | 20.3 | 2.9 | 7.6 | 4.5 | 7.2 | 7.4 |
| | Cm | 1.5 | 2.9 | 1.4 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 1900–2100 | H | 0.0 | 0.0 | 0.0 | 1.5 | 0.0 | 1.4 | 0.0 | 0.0 |
| | W | 1.5 | 8.7 | 0.0 | 17.6 | 7.2 | 15.9 | 13.6 | 14.7 |
| | SW | 39.7 | 24.6 | 17.4 | 38.2 | 30.4 | 42.0 | 28.8 | 35.3 |
| | Cm | 51.5 | 40.6 | 42.0 | 33.8 | 44.9 | 29.0 | 36.4 | 29.4 |
| | Scl | 7.4 | 26.1 | 36.2 | 8.8 | 17.4 | 11.6 | 19.7 | 20.6 |
| | Cl | 0.0 | 0.0 | 4.3 | 0.0 | 0.0 | 0.0 | 1.5 | 0.0 |
| 2200–0000 | SW | 7.2 | 1.4 | 0.0 | 0.0 | 0.0 | 2.9 | 0.0 | 1.4 |
| | Cm | 73.9 | 11.6 | 5.9 | 46.4 | 24.6 | 53.6 | 23.4 | 42.0 |
| | Scl | 18.8 | 66.7 | 63.2 | 49.3 | 63.8 | 36.2 | 48.4 | 47.8 |
| | Cl | 0.0 | 20.3 | 30.9 | 4.3 | 11.6 | 7.2 | 28.1 | 8.7 |

warm" to "comfortable". The highest time period were two hours shorter during the normal period of the thermal sensation classifications "comfortable". The highest PET (55.8 °C–65.7 °C) values were observed in LCZ 4 ("open high-rise") which occurred from 1200 CET to 1600 CET during the hot spell, which is in the "very high" human sensation category. In the normal period, the highest PET (56.1 °C–59.0 °C) hours were 2 hours shorter than during the hot spell. The lowest PET values (−1.1 °C–4.4 °C) were observed in LCZ D ("low plants") which accrued early in the morning and evening from 2100 CET to 0600 CET in the normal period, which is one category cooler than the hot spell. According to the present research result, a combination of high buildings with "low plants" increases PET spatially on a mild day. The LCZ 2 is more pleasant to spend the leisure time outdoors from 1400 CET to 1800 CET. The general conclusion of our study is that no heat stress was observed from 1900 CET to 0700 CET and the most dangerous hour for health, especially for old people, was between 1600 CET and 1700 CET in Berlin in summer 2018.

**Table 5:** a) Minimum, b) mean and c) maximum hourly human thermal sensation during the hot spell

a)

| Time (CET) | LCZ 2 | LCZ 4 | LCZ 6 | LCZ 8 | LCZ A | LCZ B | LCZ D | LCZ G |
|---|---|---|---|---|---|---|---|---|
| 0000 | Scl | Cl | Cl | Cl | Cl | Cl | Co | Cl |
| 0100 | Scl | Co | Co | Cl | Cl | Cl | Co | Cl |
| 0200 | Scl | Co | Co | Cl | Cl | Cl | Co | Cl |
| 0300 | Scl | Co | Co | Cl | Cl | Cl | Co | Cl |
| 0400 | Cl | Co | Co | Cl | Co | Cl | Co | Co |
| 0500 | Scl | Co | Co | Cl | Co | Co | Co | Cl |
| 0600 | Scl | Cl | Cl | Cl | Cl | Cl | Cl | Scl |
| 0700 | Scl | Scl | Scl | Scl | Scl | Scl | Scl | Scl |
| 0800 | Cm | Cm | Cm | Scl | Cm | Scl | Scl | Cm |
| 0900 | Cm | Scl | Scl | Cm | Cm | Cm | Cm | Cm |
| 1000 | Cm | Cm | Cm | Cm | Cm | Cm | Cm | SW |
| 1100 | Cm | Scl | Scl | Scl | Scl | Scl | Scl | Cm |
| 1200 | Cm | Scl | Scl | Cm | Cm | Cm | Cm | Cm |
| 1300 | Cm | Cm | Cm | Cm | Cm | Cm | Cm | Cm |
| 1400 | Cm | Cm | Cm | Cm | Cm | SW | Cm | SW |
| 1500 | SW | Cm | Cm | SW | SW | Cm | SW | SW |
| 1600 | SW | Cm | SW | W | W | SW | SW | W |
| 1700 | SW | SW | SW | SW | SW | SW | SW | SW |
| 1800 | Cm | Cm | Cm | SW | SW | SW | SW | SW |
| 1900 | Cm | Cm | Scl | Cm | Cm | Cm | Cm | Scl |
| 2000 | Scl | Scl | Scl | Scl | Scl | Scl | Scl | Scl |
| 2100 | Scl | Scl | Cl | Scl | Scl | Scl | Cl | Scl |
| 2200 | Scl | Cl | Cl | Scl | Cl | Scl | Cl | Scl |
| 2300 | Scl | Cl | Cl | Cl | Cl | Cl | Co | Cl |

b)

| Time (CET) | LCZ 2 | LCZ 4 | LCZ 6 | LCZ 8 | LCZ A | LCZ B | LCZ D | LCZ G |
|---|---|---|---|---|---|---|---|---|
| 0000 | Cm | Scl | Scl | Scl | Scl | Scl | Scl | Scl |
| 0100 | Cm | Scl | Cl | Scl | Scl | Scl | Cl | Scl |
| 0200 | Cm | Scl | Cl | Scl | Scl | Scl | Cl | Scl |
| 0300 | Cm | Cl | Cl | Scl | Scl | Scl | Cl | Scl |
| 0400 | Scl | Cl | Cl | Scl | Cl | Scl | Cl | Scl |
| 0500 | Cm | Cl | Cl | Scl | Cl | Scl | Cl | Scl |
| 0600 | Cm | Scl | Scl | Scl | Scl | Scl | Scl | Cm |
| 0700 | SW | SW | Cm | Cm | Cm | Cm | Cm | SW |
| 0800 | W | W | SW | SW | SW | SW | SW | W |
| 0900 | W | H | H | SW | W | H | W | W |
| 1000 | W | H | W | W | W | W | H | H |
| 1100 | SW | W | H | W | W | H | W | W |
| 1200 | W | H | W | W | W | H | W | H |
| 1300 | W | H | W | W | W | W | W | H |
| 1400 | W | H | W | W | W | H | W | H |
| 1500 | W | H | W | W | W | W | W | H |
| 1600 | W | W | H | VH | H | H | W | H |
| 1700 | W | H | W | H | H | H | H | H |
| 1800 | SW | W | SW | H | W | H | H | W |
| 1900 | SW | SW | Cm | W | SW | SW | SW | SW |
| 2000 | Cm | Cm | Cm | SW | Cm | SW | Cm | Cm |
| 2100 | Cm | Scl | Scl | Cm | Cm | Cm | Scl | Cm |
| 2200 | Cm | Scl | Scl | Cm | Scl | Cm | Scl | Cm |
| 2300 | Cm | Scl | Scl | Scl | Scl | Scl | Scl | Scl |

c)

| Time (CET) | LCZ 2 | LCZ 4 | LCZ 6 | LCZ 8 | LCZ A | LCZ B | LCZ D | LCZ G |
|---|---|---|---|---|---|---|---|---|
| 0000 | SW | Cm | Scl | Cm | Cm | Cm | Cm | Cm |
| 0100 | SW | Cm | Scl | Cm | Cm | Cm | Cm | Cm |
| 0200 | Cm | Scl | Scl | Cm | Cm | Cm | Cm | Cm |
| 0300 | Cm | Scl | Scl | Cm | Cm | Cm | Scl | Cm |
| 0400 | Cm | Scl | Scl | Cm | Cm | Cm | Scl | Cm |
| 0500 | Cm | Scl | Scl | Cm | Cm | Cm | Scl | Cm |
| 0600 | SW | Cm | Cm | Cm | Cm | Cm | Scl | Cm |
| 0700 | W | W | SW | SW | SW | W | Cm | H |
| 0800 | H | VH | H | H | H | H | H | VH |
| 0900 | H | VH | VH | H | VH | VH | VH | VH |
| 1000 | VH | VH | VH | VH | VH | VH | VH | VH |
| 1100 | H | VH | VH | H | VH | VH | VH | VH |
| 1200 | VH | VH | H | VH | VH | VH | VH | VH |
| 1300 | VH | VH | H | H | H | VH | VH | VH |
| 1400 | VH | VH | VH | VH | VH | VH | VH | VH |
| 1500 | H | VH | VH | VH | VH | VH | VH | VH |
| 1600 | H | VH | VH | VH | VH | VH | VH | VH |
| 1700 | H | VH | VH | VH | VH | VH | VH | VH |
| 1800 | W | H | H | VH | H | VH | VH | VH |
| 1900 | W | W | SW | H | W | H | W | W |
| 2000 | SW | SW | Cm | W | SW | SW | SW | SW |
| 2100 | SW | SW | Cm | SW | Cm | SW | Cm | SW |
| 2200 | SW | SW | Cm | Cm | Cm | SW | Cm | SW |
| 2300 | SW | Cm | Cm | Cm | Cm | Cm | Cm | Cm |

Co : Cold; Scl : Slightly cool; Cl : Cool; Cm : Comfortable; SW : Slightly warm; W : Warm; H : High; VH : Very high


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## Abbreviation list

| | |
|---|---|
| BMBF | Federal Ministry of Education and Research in Germany |
| C | Centigrade |
| h | hour |
| ha | hectare |
| K | Kelvin |
| LCZ | Local Climate Zone |
| m | meter |
| min | minute |
| mm | milimeter |
| PET | Physiologically equivalent temperature |
| $T_{max}$ | Maximum Temperature |
| SVF | Sky View Factor |

# A Appendix

**Table 6:** Micrometeorological stations in Berlin

| Number | Station Name | Latitude degree | Longitude degree | Elevation (m) | LCZ | Operated since YYYYmmdd | SVF |
|---|---|---|---|---|---|---|---|
| 1 | fasanen | 52.51 | 13.33 | 34 | 2 | 20000801 | 0.234 |
| 2 | jagow | 52.52 | 13.33 | 37 | 2 | 20170405 | 0.264 |
| 3 | schiller | 52.51 | 13.32 | 35 | 2 | 20170106 | 0.513 |
| 4 | galvani | 52.52 | 13.32 | 34 | 2 | 20170113 | 0.064 |
| 5 | marzahnwuhle | 52.55 | 13.59 | 55 | 4 | 19990723 | 0.426 |
| 6 | fichtenberg | 52.46 | 13.31 | 66 | 6 | 20101101 | 0.308 |
| 7 | amselsw | 52.61 | 13.29 | 39 | 6 | 20160823 | 0.46 |
| 8 | amselgrund | 52.61 | 13.29 | 40 | 6 | 20160823 | 0.279 |
| 9 | amselne | 52.61 | 13.29 | 42 | 6 | 20161127 | 0.355 |
| 10 | biesdorf | 52.52 | 13.55 | 56 | 6 | 20161027 | 0.701 |
| 11 | petit | 52.61 | 13.41 | 52 | 6 | 20161104 | 0.348 |
| 12 | martinhoffm | 52.49 | 13.46 | 34 | 6 | 20170104 | 0.019 |
| 13 | waldschule | 52.5 | 13.26 | 59 | 6 | 20170403 | 0.259 |
| 14 | montan | 52.58 | 13.35 | 45 | 8 | 20161027 | 0.496 |
| 15 | zerpensch | 52.61 | 13.37 | 49 | 8 | 20161114 | 0.435 |
| 16 | landsberger | 52.53 | 13.49 | 59 | 8 | 20161117 | 0.93 |
| 17 | motard | 52.53 | 13.26 | 34 | 8 | 20161130 | 0.379 |
| 18 | buckower | 52.41 | 13.39 | 46 | 8 | 20161208 | 0.446 |
| 19 | tegelforoff | 52.61 | 13.27 | 40 | A | 20000518 | 0.308 |
| 20 | preissconif | 52.65 | 13.29 | 52 | A | 20161012 | 0.11 |
| 21 | tegelforest | 52.61 | 13.29 | 55 | A | 20161024 | 0.036 |
| 22 | preissout | 52.65 | 13.29 | 55 | A | 20170816 | 0.174 |
| 23 | botangarden | 52.45 | 13.3 | 51 | B | 19980929 | 0.47 |
| 24 | zoo | 52.51 | 13.34 | 35 | B | 20170113 | 0.114 |
| 25 | gatow | 52.47 | 13.14 | 50 | D | 19991124 | 0.578 |
| 26 | buchholzer | 52.61 | 13.4 | 52 | D | 20161104 | 0.563 |
| 27 | elisabethaue | 52.61 | 13.41 | 52 | D | 20161104 | 0.62 |
| 28 | mueggelsee | 52.44 | 13.63 | 35 | G | 20111005 | 0.504 |
| 29 | wannsee | 52.43 | 13.18 | 36 | G | 20030813 | 0.486 |
| 30 | teglersee | 52.57 | 13.26 | 35 | G | 20091026 | 0.61 |
| 31 | pichelsdorf | 52.51 | 13.2 | 31 | G | 20071004 | 0.574 |
| 32 | rctegel | 52.59 | 13.27 | 33 | G | 20161016 | 0.51 |

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