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Urban Meteorology

The footprint of heat waves and dry spells in the urban climate of Würzburg, Germany, deduced from a continuous measurement campaign during the anomalously warm years 2018–2020

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Abstract

The present study contributes to the issue of the urban heat island (UHI) effect with its possibly associated thermal stress for city dwellers and its potential mitigation during heat waves and dry spells in Central Europe. It is based on meteorological measurements along an urban transect in the city of Würzburg, Germany. Due to its topographic and structural situation, Würzburg is prone to an intense urban heat island (UHI). The measurements have started in 2018 and, hence, cover a period that was characterized by record high temperatures and long dry spells in Central Europe. Particularly on days with a maximum air temperature of more than 25 °C, an intense UHI was observed with the highest amplitude in the afternoon and, even more, during the evening hours. The highest measured difference between the densely built inner city and the outskirts was 8.2 °C. The UHI during summer is noticeably more pronounced, especially during the evening hours, when the regional background climate is anomalously warm and dry. This can be ascribed to anticyclonic weather types that prevailed over Central Europe during summertime between 2018 and 2020. The cooling effect of urban trees, in this case *Tilia cordata*, on near-surface air temperature amounts to partly more than 2 °C and, hence, mitigates the UHI locally, especially at noon and in the early afternoon. However, the cooling rate is only half as much when the trees suffer from water stress. Thus, an appropriate management of city's green infrastructure represents a useful strategy to mitigate the strength of the UHI and the heat stress in Central Europe.

Keywords: urban climate, long-term monitoring, city trees, heat waves, climate change, Germany

1 Introduction

Cities and settlements around the world show higher temperatures than their non-urban surroundings. This effect is known as the urban heat island (UHI) and generally well explored by manifold studies (Kim and Brown, 2021). (Oke, 1973) found out that the intensity of the UHI effect depends on the population size of the city. By remote sensing, SUHI (surface urban heat island) effects of up to 15 °C have been detected for surface temperatures, e.g. in Athens or Latin-American cities, while in situ measurements showed lower values for air temperatures (Palme, 2021; Kourtidis et al., 2015). Due to ongoing climate change, an intensification of the urban heat island effect is expected to occur, especially if cities are highly sealed and have a low cover of vegetated areas (Levermore et al., 2018; Rahman et al., 2020). This will lead to more frequent and/or intense heat stress in the city area. According to the high population density, heat waves in cities can lead to more medical emergencies and a higher mortality (Wondmagegn et al., 2021; Xu et al., 2016).

Due to their specific building structure, city quarters differ in their local climatological characteristics. This mode is for example used in the Local Climate Zone (LCZ) model (Stewart and Oke, 2012). Depending of the proportion of sealed to green areas, there are substantial spatial variations of meteorological parameters like air temperature and humidity (Lozán et al., 2019b; Pauleit et al., 2017). (Rahman et al., 2020) investigated these variables for the city of Würzburg and found clear differences, not only between the city center and the outskirts, but also at finer spatial scales involving river sides and park areas.

Generally, the UHI results from a modification of the radiation budget and the surface energy balance in urban areas compared with the rural environment (Lozán et al., 2019a; Oke, 1973; Marzluff et al., 2008). In

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addition, the topography around the city and its building structure and density together with the extent of green and blue infrastructure play an important role (Pauleit et al., 2017; Lozán et al., 2019b). This study focuses on the city of Würzburg in the southern part of Germany because it is assumed to be a paradigm for an enhanced UHI effect within a hotspot region of climate change. Indeed, the lower Franconian region around Würzburg is known as a very warm and dry region in central Germany due to its topographic situation (Schönbein et al., 2020). Regional climate models project an above-average warming rate and a dramatic drying tendency during the warm season (Rauh and Paeth, 2011; Paeth and Pollinger, 2020). This implies a substantially enhanced frequency of heat waves, dry spells and tropical nights as major precursors of heat stress, especially in urban areas (Paeth et al., in review). Furthermore, the inner city is highly sealed, barely greened and located in a deep basin with low horizontal and vertical mixing of air masses (Rahman et al., 2022). Using the simple population-related formula for European settlements by (Oke, 1973) an urban heat island effect of 6.2 °C can be anticipated for Würzburg.

Our study is based on a continuous monitoring of the meteorological conditions inside and outside of Würzburg since 2018. Thus, the measurement campaign comprises a series of record-warm and -dry years between 2018 and 2020. This offers the opportunity to assess the urban climate of a highly exposed Central European city during a period that foreshadows the expected regional climate conditions into the 21st century (Paeth et al., in review). Another novel aspect is the monitoring network itself: it is set up along an urban-rural transect to assess the general UHI effect and includes pairs of neighboring stations with open-sky and tree-canopy conditions, respectively, to quantify the cooling effect by city trees. In detail, the study comprises three main objectives: (1) to assess critical urban climatological indicators such as heat days and tropical nights during the occurring heat waves, (2) to determine the intensity as well as the seasonal and diurnal variations of the UHI effect in Würzburg, and (3) to quantify the mitigation potential of city trees in terms of urban heat stress due to their cooling effect on the air temperature.

The next section is dedicated to the considered data and methods, including the established monitoring network. Results are described in Section 3 and discussed in Section 4. Section 5 provides the main conclusions and a short outlook with respect to ongoing work.

2 Data and Methods

2.1 Location and urban structure of Würzburg

Würzburg is located in the middle of Germany, more precisely in the northwest of Bavaria (Fig. 1) and has 129,500 inhabitants (City of Wuerzburg, 2021). It is a medium-sized and densely built city, located in a deep valley of the river Main which gives the city a distinct urban climate. The mean climate over the 1981–2010 reference period is characterized by an annual mean temperature of 9.6 °C and a total precipitation of 601 mm (DWD 2021a). It is classified into the Cfb-climate zone of the Koeppen/Geiger climate classification (Kottek et al., 2006). Topographically, Würzburg is surrounded by several low mountain ranges, i.e. the Spessart in the west, the Rhön in the north and the Steigerwald in the east. Due to resulting windward/lee effects, Würzburg is known as a particularly warm and dry city compared to other cities in Germany and lies within a potential hotspot of climate change (Rauh and Paeth, 2011; Paeth et al., in review). Furthermore, the city exhibits some specific features that make it particularly suitable for a study on urban heat island effects and possibly associated thermal stress on residents and local climate gradients. First of all, there is an inner-city core with a diameter of 1 km, a high degree of sealing and only few areas with urban green. The inner city is surrounded by a park area called Ringpark, which demarcates the extent of the former city wall and is characterized by low sealing and dense tree population. Thereafter, the building density gradually declines and the proportion of urban green increases towards the suburban outskirts in a radius of 5 km. The river Main is also one of the special features that affects the inner-city area.

2.2 Established station network

In total, we installed eight weather stations in and around the city of Würzburg where the local climate is measured along an urban transect (Fig. 1 and Table 1). The meteorological observations are supplemented by tree measurements at six of the eight stations. At the tree sides we measured the temperature and humidity under the tree canopy and parameters that are relevant for the tree physiology like the soil moisture, the sap flow and the trunk growth. For more details of the tree measurements see (Rahman et al., 2020). The sites were selected by the sealing degree and the proportion of urban green as well as local features, e.g. the proximity to the river Main. The aim was to achieve a representative transect for assessing the urban climate gradient of Würzburg across different city districts, at which both the weather and the tree physiology were measured.

Fig. 1 shows an elevation gradient with increasing height from the river Main (174 m) to the rural areas of Gerbrunn (268 m). Due to the increasing altitude of the topography, we get some slight values of slope in the terrain, but still below 1 % around our stations (Table 1): the slope ranges between 0.53° at Marktplatz and 0.95° at Rottendorfer Tor. The aspect of the terrain is mostly directed westward, except for Rottendorfer Tor (northwest) and Gerbrunn (northeast). Table 1 also shows the proportion of green and sealing around the stations. As to be expected, there is a high proportion of sealing with very low parts of urban green in the downtown area,

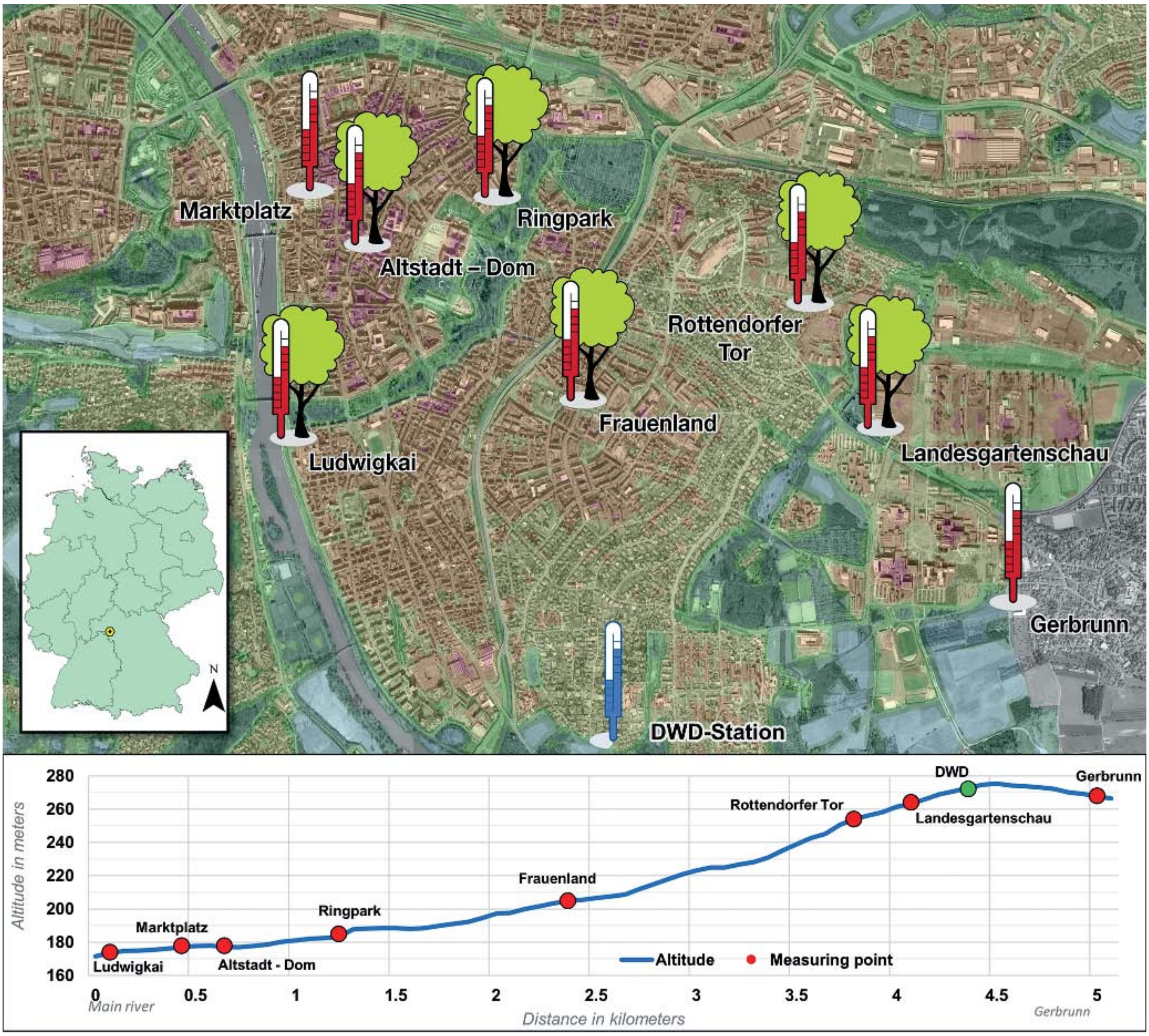

Figure 1: Location of the city of Würzburg within Germany, locations of the eight meteorological stations inside and outside of Würzburg, the official station of the German Weather Service (DWD) and their elevation profile.

Table 1: Morphometric characteristics of the meteorological stations inside and outside of Würzburg. The proportion is classified by green: nearly none < 5 %, very high > 40 %, sealing: low < 50 %, very high > 90 %.

Location	Latitude	Longitude	Altitude [m]	Slope [°]	Aspect [dir]	Proportion of		Type
						green	sealing	
Ludwigkai	49,78478	9,92804	174	0,85	west	medium low	medium high	riverbank
Marktplatz	49,79465	9,92968	178	0,53	west	nearly none	very high	downtown
Altstadt – Dom	49,79275	9,93256	178	0,83	west	very low	very high	downtown
Ringpark	49,79358	9,94013	185	0,59	west	very high	medium	park
Frauenland	49,78628	9,94892	205	0,77	west	medium	high	transition
Rottendorfer Tor	49,79085	9,96318	254	0,95	northwest	medium	medium	suburb
Landesgartenschau	49,78613	9,96669	262	0,87	west	very high	low	rural
Gerbrunn	49,78019	9,97645	268	0,89	northeast	very high	low	rural

interrupted by the Ringpark. The transition area, represented by the station Frauenland, ties on this with a slight reduction of the sealing degree and an increase of urban green. The proportion of sealing decreases further with the suburb area at Rottendorfer Tor and there is also a higher share of urban green. By reaching the rural area at the top of the hill at Landesgartenschau and Gerbrunn, sealing declines to a low value while the proportion of green is very high.

At each of the eight locations we installed a weather station to collect the meteorological data using high-precision instruments. We decided to use streetlamps and their power supply for attaching the weather stations in the urban area. The measurements of air temperature, humidity (combined, Campbell CS 215) and precipitation (Campbell ARG 100 rain gauge) were carried out at a height of three meters above the ground. This height was selected to avoid damages by vandalism. At an altitude of 7 to 10 meters above ground, depending on the length of the streetlight masts, the instruments for global radiation (Campbell CS300 Pyranometer), wind-speed and wind direction (both RM Young wind sentry model 03002-5) were installed. At the sites of Marktplatz, Landesgartenschau and Gerbrunn (see Fig. 1) air pressure was also measured (Vaisala Barocap PTB110). The measurements were taken every minute, except for wind speed which is taken in a two-second interval in order to achieve better results for gusts. After 10 minutes the maximum, minimum and average values for each parameter were stored on a CR300 datalogger and sent instantly to a data server via an FTP client.

To check the data quality and plausibility, we used several control steps. Missing or plainly implausible data values, e.g., due to malfunction of the stations, were filtered by a R and Fortran script. Conspicuous values were checked manually by using high resolution weather maps or weather service data for Würzburg. The measurements took place continuously since 2018. For this study we addressed the time slot from January 2018 to July 2021.

2.3 Methods

The main focus of the present study was on near-surface air temperature and the associated manifestations of the UHI effect during the seasonal and diurnal cycle. In addition, various climatological indicators are considered. A climatological indicator day is defined by a threshold value of a given meteorological variable that is exceeded or undercut and is meant to give an overview of local or regional climate (change) characteristics. Such thresholds often refer to temperature and precipitation anomalies or extremes (DWD, 2021b). We determined the number of 'warm' climatological days such as summer days ($T_{max} > 25\,°C$), heat days ($T_{max} > 30\,°C$) and tropical nights ($T_{min} > 20\,°C$ as well as the number of 'cold' climatological days like frost days ($T_{min} < 0\,°C$) and ice days ($T_{max} < 0\,°C$) (DWD 2021b). Their occurrence is only analyzed here for the anomalously warm and dry years 2018, 2019 and 2020.

For all climatological indicators, monthly means were computed and compared with respective long-term averages from a weather station of the German Weather Service (DWD) that is operating since the late 1950s at the southern edge of the study region displayed in Fig. 1. Elevation and environmental conditions of this DWD station are very close to the stations Landesgartenschau and Gerbrunn of our own meteorological network (Fig. 1). The reference period for anomalies of observed temperature, precipitation, relative humidity, and climatological indicators extends from 1981 to 2010.

The difference between the stations Marktplatz and Gerbrunn is generally used to assess the UHI of Würzburg. We selected these two stations to gain the largest temperature contrast between the highly sealed inner-city core at Marktplatz and the rural outskirts in Gerbrunn. Due to the elevation differences of about 100 meters between the stations, it is necessary to adjust the air temperature values. This is done by using the potential temperature computed via the Poisson equation for all stations (Bott, 2012). To compare the climatological attributes of each location we calculated mean values. Mean temperature and humidity refer to all valid 10-minute values over the data period. The average of the daily highest temperature difference of station 'X' and the 'Marktplatz' is used for the UHI. For the cooling effect of the trees only the values of the '*Tilia cordata*' sites were used because it is present at most stations. The mean tree cooling rate was calculated by using all daily maximum values of the temperature contrast between the respective tree-canopy station and the open-sky weather station. The mean cooling rate at sunset was computed using the temperature values one hour before and two hours after sunset to avoid microscale interferences.

3 Results

3.1 The record-warm years 2018–2020 in terms of temperature, precipitation, and humidity

Monthly anomalies of temperature, precipitation and relative humidity are displayed for station Landesgartenschau (Fig. 2) in order to illustrate the local footprint of the unusually warm and dry years 2018–2020 in Central Europe. It can be seen that only four of the 36 months were cooler than on average, the remaining 32 months were warmer (Fig. 2, top panel). Particularly the summer months of 2018 were substantially too warm with up to 3 °C. But also, June 2019 shows an anomaly of +3.5 °C, whereas May 2019 was cooler than on average. The highest positive temperature anomaly was measured in April 2018, with about 4.5 °C. During the study period, 27 out of the 36 months revealed negative precipitation anomalies, nine were moister than the long-term average (Fig. 2, middle panel). Half of the dry

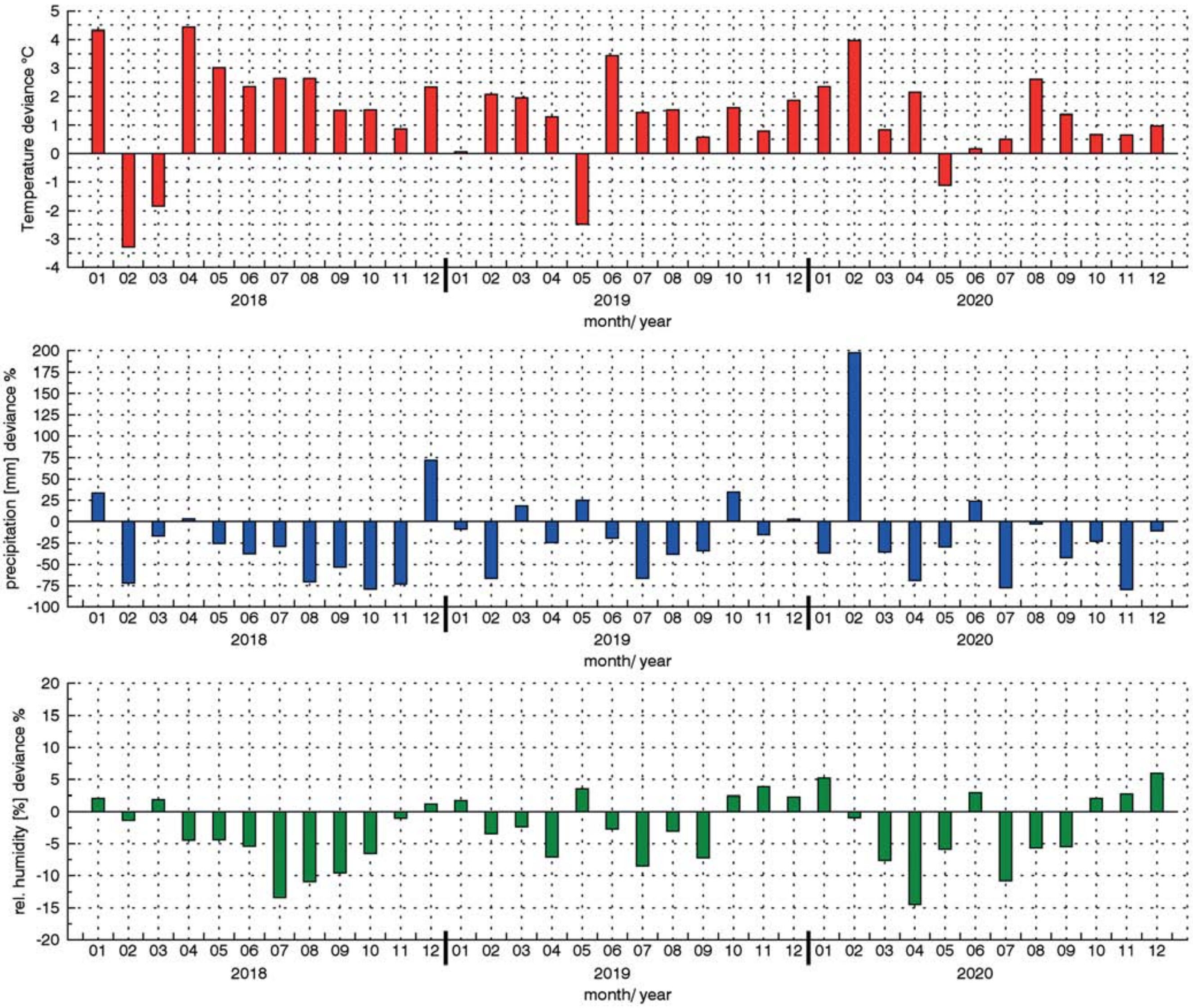

Figure 2: Monthly anomalies of air temperature, precipitation and relative humidity during the years 2018–2020 at station Landesgartenschau with respect to the 1981–2010 long-term mean at the nearby DWD station.

months show strictly negative anomalies with less than 35 % of the usual monthly rainfall totals, especially October 2018 with only 20 % from just two precipitation events. Deficient precipitation was observed particularly during summer, when the mean seasonal cycle of precipitation is typically at its maximum (DWD 2021a). Positive anomalies were usually less extreme since 2018, except for February 2020 with a remarkable surplus of almost 200 % compared with the long-term mean.

In terms of relative humidity negative anomalies prevailed in 23 out of 36 months (Fig. 2, bottom panel). The strongest negative anomalies can be found in April 2020 with almost 15 % less relative humidity than on average. But also, summer 2020 experienced a consistent negative anomaly of relative humidity, particularly in July. It is noticeable that the lowest differences of relative humidity from the reference period occurred during the winter period, although the temperatures were higher than normal during this time. In summary, there is a seasonal cycle in the monthly anomalies of relative humidity during our study period with below/above average values during the warm/cold season.

3.2 The record-warm years 2018–2020 in terms of climatological indicators

In this study, we refer to three indicators of heat, two indicators of frost and one indicator of dryness (see Subsection 2.3). In Würzburg we measured an above average number of warm climatological days in each of the three observational years and at each station. Accordingly, there was a below average number of cold climatological days. Table 2 provides a first glimpse of the urban climate of Würzburg by comparing the counts of indicator days of all stations. Especially in 2018, there

Table 2: Counts of climatological indicator days during the years 2018–2020 at all stations and comparison with the 1981–2010 long-term mean at the nearby DWD station.

Climatological indicator day		Summer days ($T_{max} \geq 25\,°C$)	Heat days ($T_{max} \geq 30\,°C$)	Tropical nights ($T_{min} \geq 20\,°C$)	Frost days ($T_{min} < 0\,°C$)	Ice days ($T_{max} < 0\,°C$)	Days without precipitation ($\sum_{day} = 0\,mm$)
Ludwigkai	2018	99	29	5	60	5	223
	2019	66	28	2	58	5	219
	2020	62	14	0	63	2	211
Marktplatz	2018	112	53	7	45	5	234
	2019	84	33	6	51	4	222
	2020	83	22	6	42	1	225
Dom	2018	108	43	9	44	5	235
	2019	78	30	7	46	4	220
	2020	79	18	6	39	2	218
Ringpark	2018	104	44	4	55	5	227
	2019	69	27	6	53	4	208
	2020	62	12	2	49	3	212
Frauenland	2018	102	33	4	60	5	243
	2019	73	26	5	58	5	225
	2020	67	12	2	53	2	241
Rottendorfer Tor	2018	96	31	4	61	8	237
	2019	68	25	3	57	5	220
	2020	62	13	0	55	3	209
Landesgartenschau	2018	105	32	4	70	8	238
	2019	69	27	1	62	5	217
	2020	63	15	0	68	2	206
Gerbrunn	2018	104	33	4	69	6	228
	2019	68	27	1	65	5	208
	2020	65	14	0	63	2	208
DWD average	1981–2010	47,7	10,4	< 1	77,3	19,3	194,9

was an exceptionally high number of heat days at Marktplatz, namely 53 days which is five times higher than the average. At Landesgartenschau it was three times higher compared to the long-term mean at the DWD station. We also observed 112 summer days, which is twice as many as during the reference period 1981–2010. In addition, several tropical nights were measured, whereas they barely occurred during the 1981–2010 period. In 2018 we got seven to nine tropical nights in the inner-city area and still four in the outskirts. In 2019 and 2020, the occurrence of tropical nights was mainly limited to the mostly sealed stations from Marktplatz till Frauenland, one of which exceeded a minimum temperature of 25 °C. We also see a lower occurrence of heat induced indicator days at the stations located near the water body of the Main river and the park side, although they are close to the downtown.

The number of frost days and ice days were clearly below the long-term average at both stations (Table 2). The highest reduction was found at Marktplatz and Dom, especially when counting the ice days. Typically, there are 19.3 ice days per year in Würzburg, yet in the city center we measured five in 2018 and only one in 2020. At Landesgartenschau, eight and two days were counted in 2018 and 2020, respectively. A similar picture occurs for frost days: compared with the climatological mean of 77.3 days per year we observed a slightly lower number with 70 to 62 days at station Landesgartenschau, while Marktplatz showed clearly less events with 42 to 51 frost days per year during the 2018–2020 study period. We also see here a distinctive higher number of cold indicator days at the sides near the river- and parkside. There are up to 30 % more frost days at Ludwigkai and Ringpark in comparison with the downdown stations. However, the occurrence of ice days is nearly the same.

The days without precipitation differ only slightly between the two locations because rainfall-suppressing weather types such as anticyclones typically extend over a large area (Table 2). Especially in 2018, the number of dry days was considerably higher than normal (238 versus 195 days). This means that almost two thirds of all days during the year did not experience any rainfall. In 2020 it was about 55 % of all days. None of the considered years achieved the normal number of rainfall days per year. Sometimes we see differences in the number of dry days within a year between some stations, e.g., in 2018 between Frauenland (243) and Ludwigkai (223).

Fig. 3 illustrates the seasonal cycle and inter-annual variations of warm, cold, and dry indicator days at station Marktplatz where the most striking anomalies occurred. Summer days occur during a period from April until October with a peak in July. Heat days are more confined to the warm season from May or June until the beginning of September. While the years 2018 and 2020 exhibit a somewhat Gaussian distribution, the year

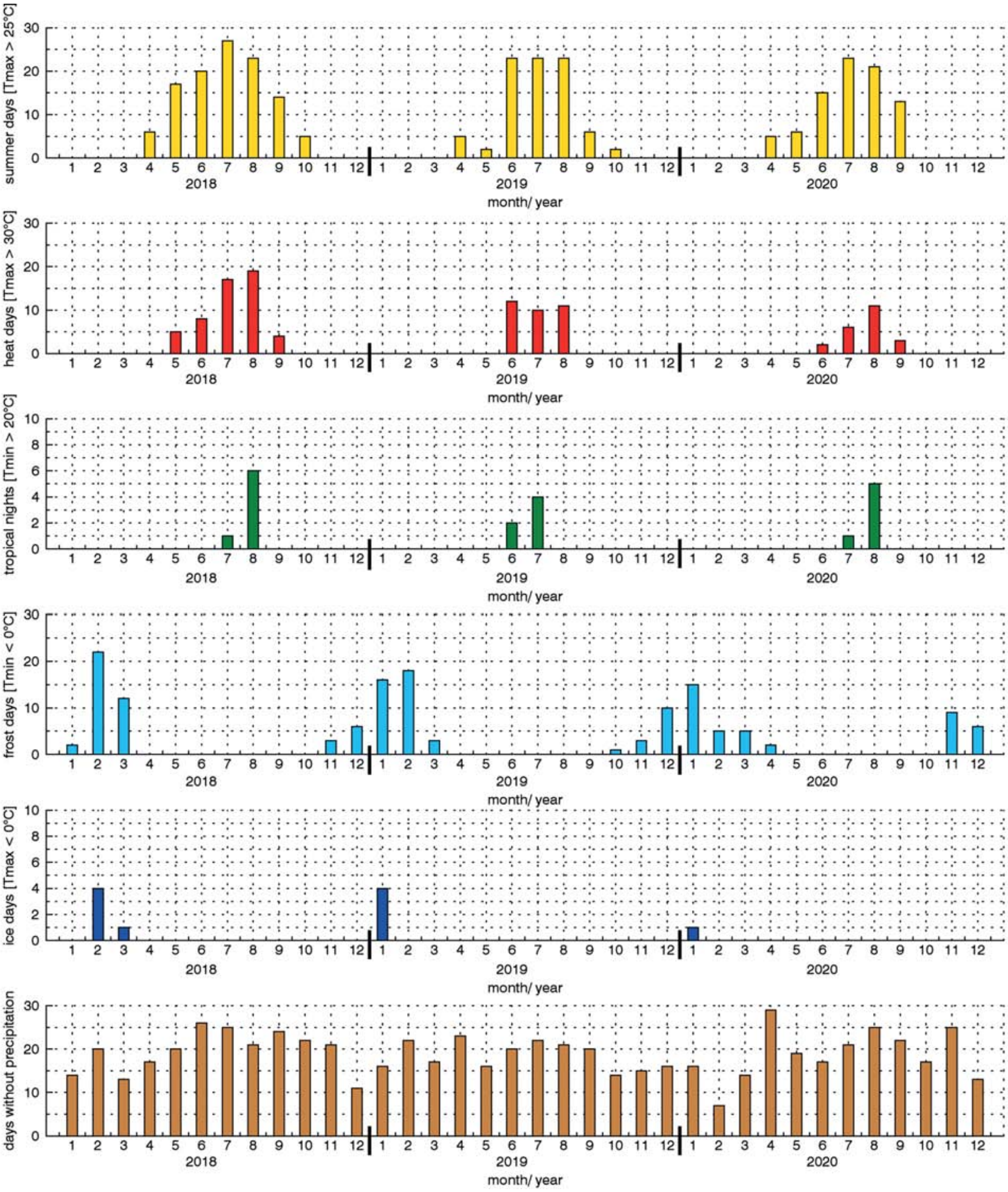

Figure 3: Monthly means of climatological indicator days during the 2018–2020 period at station Marktplatz.

2019 is close to a uniform distribution with no summer month standing out. Tropical nights are restricted to the June to August period of the year. The cold climatological indicators occur during autumn, winter and early spring. Frost days usually happen at a period from October until April, mostly with a peak in January or February. Ice days were only observed in January and February. Days without precipitation peak between spring and summer. Nonetheless, the seasonal cycle of dry days is much less prevalent than for thermal indicator days. As to be expected, the number of dry days is related to the anomalies of monthly precipitation (Fig. 2) because months with a high precipitation deficit tend to have a higher number of days without precipitation. Particularly, April 2020 should be mentioned here with its high precipitation deficit (only 8 % of long-term mean rainfall) and a total of 28 out of 30 days without precipitation.

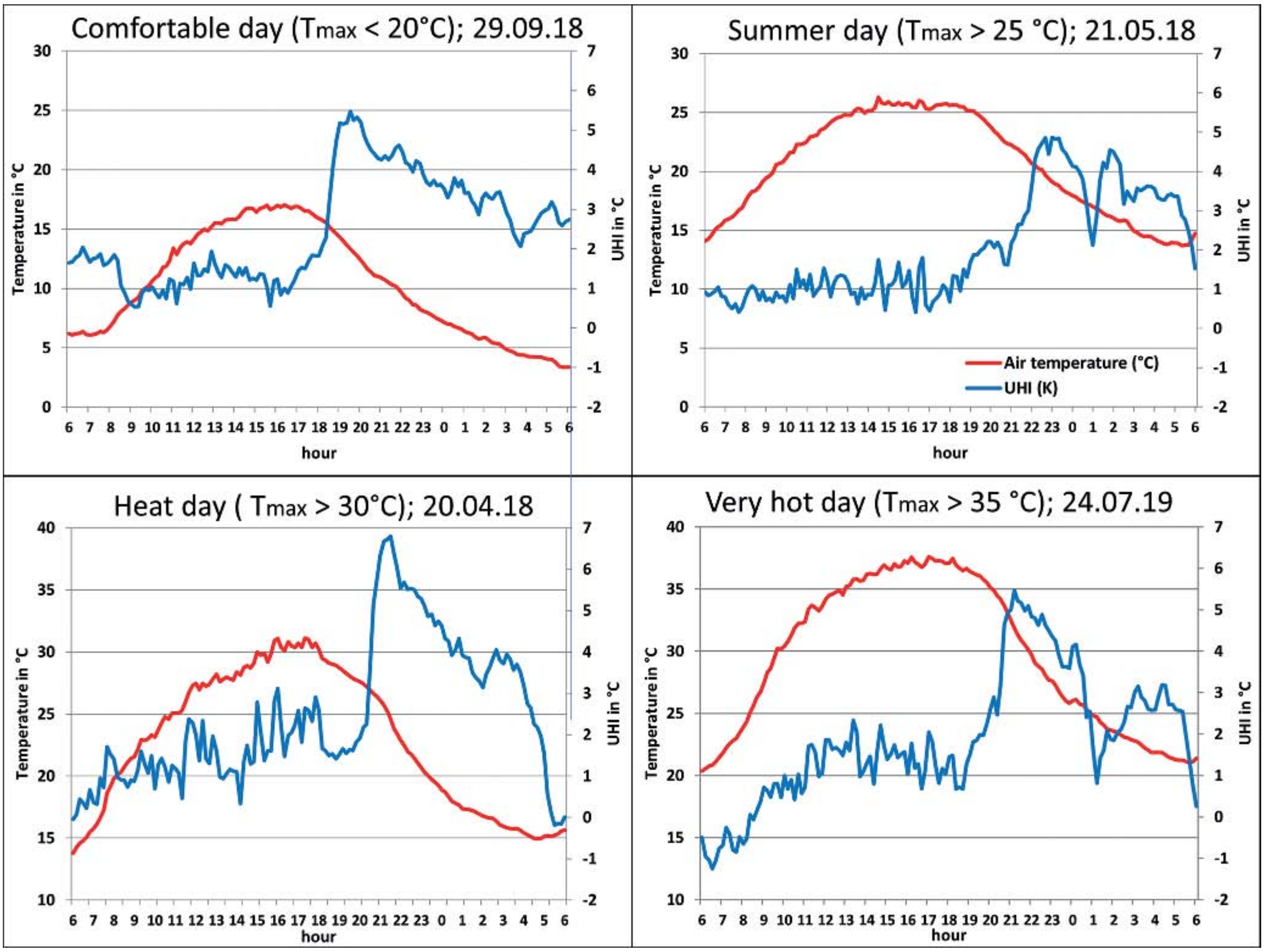

Figure 4: Diurnal temperature (red) and UHI (blue) variations over four specific days during the 2018–2020 period. The temperature time series refer to station Gerbrunn and the UHI time series to the difference between Marktplatz and Gerbrunn.

3.3 Characteristics of the UHI in Würzburg

To gain a better understanding of the UHI characteristics during the year, we first investigated days with different daily maximum temperatures. To avoid any bias by weather phenomena days with nearly the same meteorological conditions were used, i.e., a central anticyclone above Germany, cloud-free conditions and a daily maximum wind speed lower than three Beaufort. Furthermore, there was no precipitation for at least 24 hours before the considered day. Thus, a nearly ideal and undisturbed diurnal cycle of temperature and the resulting UHI effect can be expected. Overall, a comfortable day ($T_{max} < 20\,°C$), a summer day ($T_{max} > 25\,°C$), a heat day ($T_{max} > 30\,°C$) and a very hot day ($T_{max} > 35\,°C$) were selected (Fig. 4). The basic shape of the diurnal temperature cycle barely differs between the selected days, while the different temperature levels are clearly visible. Under comparable weather type conditions, the four selected days also exhibit a rather similar diurnal cycle of the UHI: a strong temperature contrast occurs between the city center and the outskirts towards the evening hours. The UHI remains on a high level for only 1–2 hours and slowly reduces during the night. The temperature contrast is sometimes balanced out in the morning hours before sunrise. The UHI of Würzburg tends to be more expressed on heat and very hot days, although this still needs to be corroborated based on a larger sample (see below).

A more general perspective on the UHI of Würzburg is presented in Fig. 5, using an isopleth diagram with the seasonal cycle along the x-axis and the diurnal cycle along the y-axis. Due to the later operation of the station Gerbrunn, there were no data available until June 2018, but here we refer to an extended measurement period until July 2021 (see Subsection 2.3). In order to remove a part of the very high frequency variability on the basis of the original 10-minutes data, the diagram has been smoothed to hourly data. As a consequence, the peak amplitudes of the UHI of up to 8.2 °C have also been smoothed. It is obvious that the UHI follows a typical diurnal and seasonal cycle. The UHI is more pronounced during the warm seasons, with an exception in January and February 2019 where the effect in the evening hours was comparable to the summer situation. The diurnal cy-

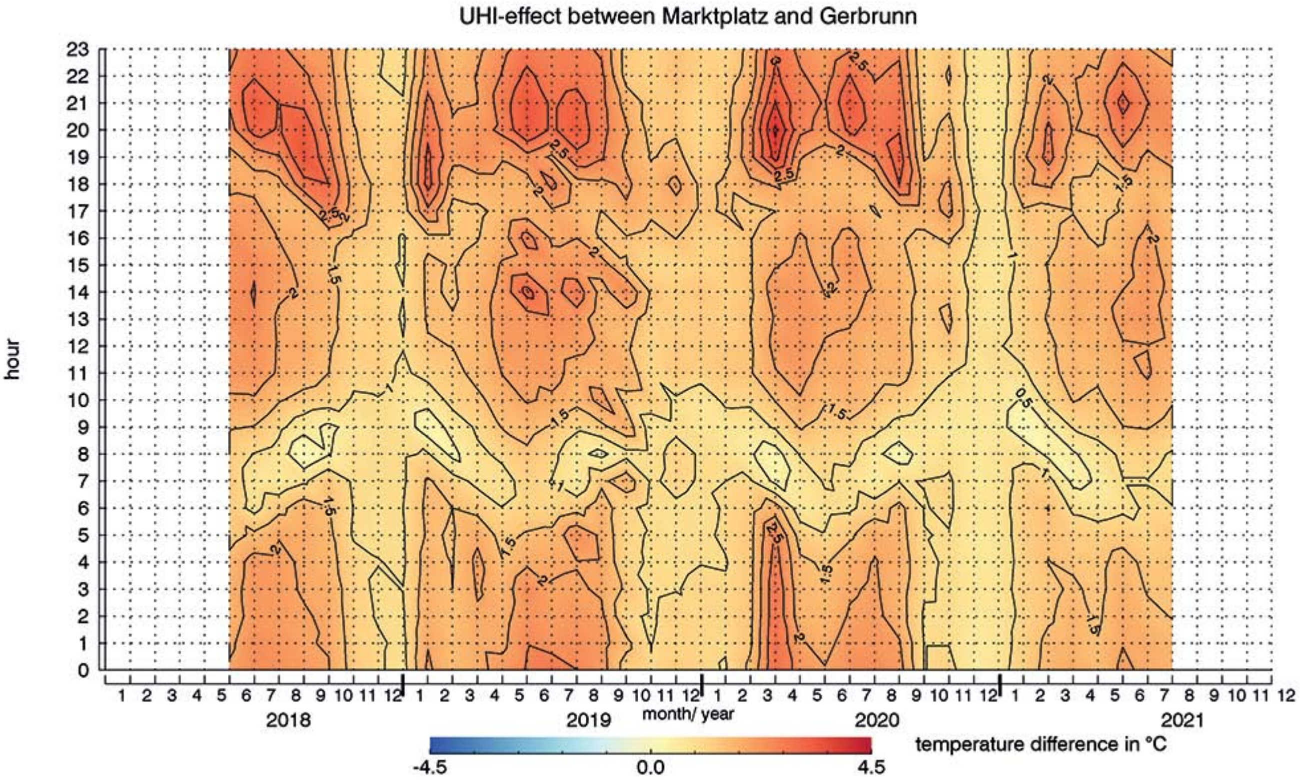

Figure 5: Isopleth diagram of the UHI-effect in °C between stations Marktplatz and Gerbrunn during the observational period until July 2021. Note that station Gerbrunn has operated with a time delay of five months.

cle is also more apparent between spring and autumn and almost vanishes in November and December. The maximum UHI effect is usually reached in the evening and early night, with a second maximum in the afternoon during the summer months. The temperature contrast between the inner-city and the outskirts almost disappears in the morning at sunrise. Throughout the summer, there is an average UHI effect of more than 3.5 °C around sunset, in winter it is more a constant difference all over the day with values around 1.5 °C. Concerning the year-to-year differences, the anomalously warm years 2018, 2019 and 2020 came along with a noticeably more intense UHI in Würzburg than the more normal spring and early summer months in 2021.

Fig. 6 is dedicated to the dependence of the UHI effect in Würzburg on the daily maximum temperature at station Marktplatz. It can be seen that there is a positive linear trend. The regression model accounts for about 34 % of the total variance and is statistically significant at the 1 % level. The highest UHI amplitudes were found when the daily maximum temperature exceeds 25 °C. According to the regression line, a maximum temperature of 20 °C generates an UHI of around 3 °C, while 30 °C come along with 4 °C of UHI. It should also be noted that there is a relatively high dispersion around these mean estimates, implying that maximum temperature is competing with other meteorological factors in shaping the UHI of Würzburg. The highest UHI amplitude of 8.2 °C was measured on a heat day with a maximum temperature of 31.5 °C (29th of August 2019). UHI values of more than 6.5 °C were only observed on days with more than 20 °C. The warmest day we measured had a maximum daily temperature of 40.3 °C and generated an UHI-effect of 6.3 °C (25th of July 2019). In general, the urban climate effects are much less apparent on relatively cool days. However, even cold days can cause strong UHI effects, e.g., a day in January with a daily maximum temperature of 3.1 °C and an UHI of 4.2 °C (21st of January 2019).

The continuous monitoring of the urban climate of Würzburg also allows us a statistical assessment of the general weather situations that strengthen or mitigate the UHI. This issue is of relevance when it comes to the question of how the urban heat island or heat stress may respond to future climate change, e.g. via a modified frequency of specific weather types projected by climate models until the end of the 21st century (Kučerová et al., 2017; Straub et al., 2019). Fig. 7 displays the maximum UHI effect between station Marktplatz and three suburban stations as a function of eight dominating weather types that together account for 35 % of all days of the year. The weather types are determined according to the qualitative Hess-Brezowsky classification approach (Hess and Brezowsky, 1952) that is updated and made available at a daily scale by the DWD (https://www.dwd.de). It is obvious that anticyclonic weather

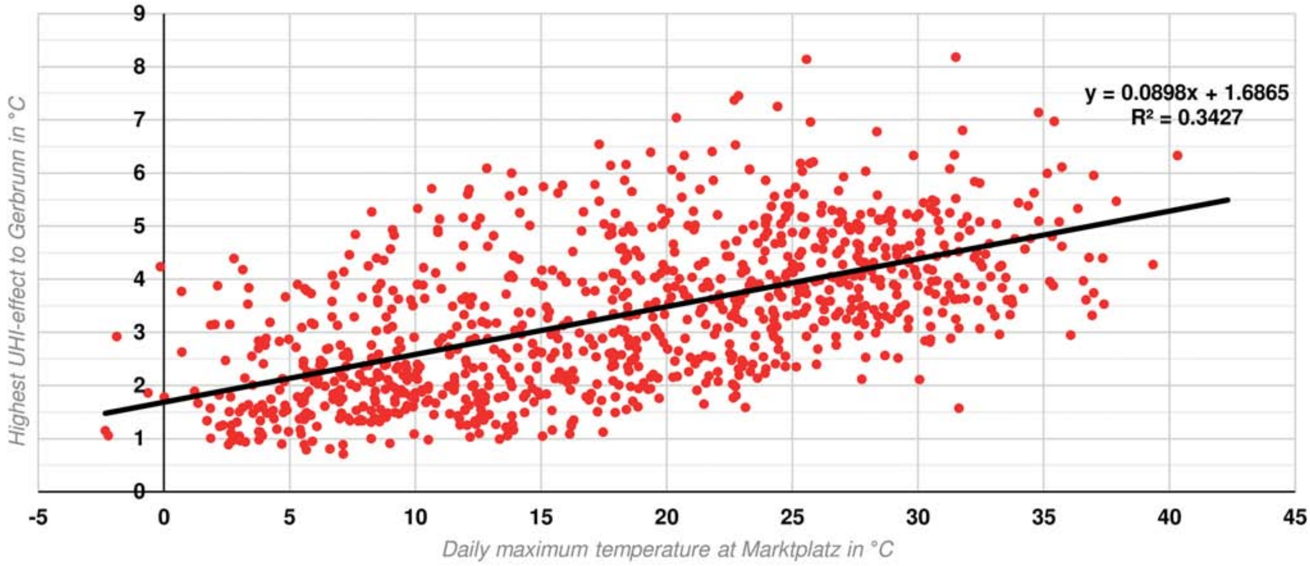

Figure 6: Observed UHI effect of Würzburg (station Marktplatz minus Gerbrunn) as a function of daily maximum temperature at station Marktplatz. The trend line refers to a linear regression and R^2 denotes the explained variance of the regression model.

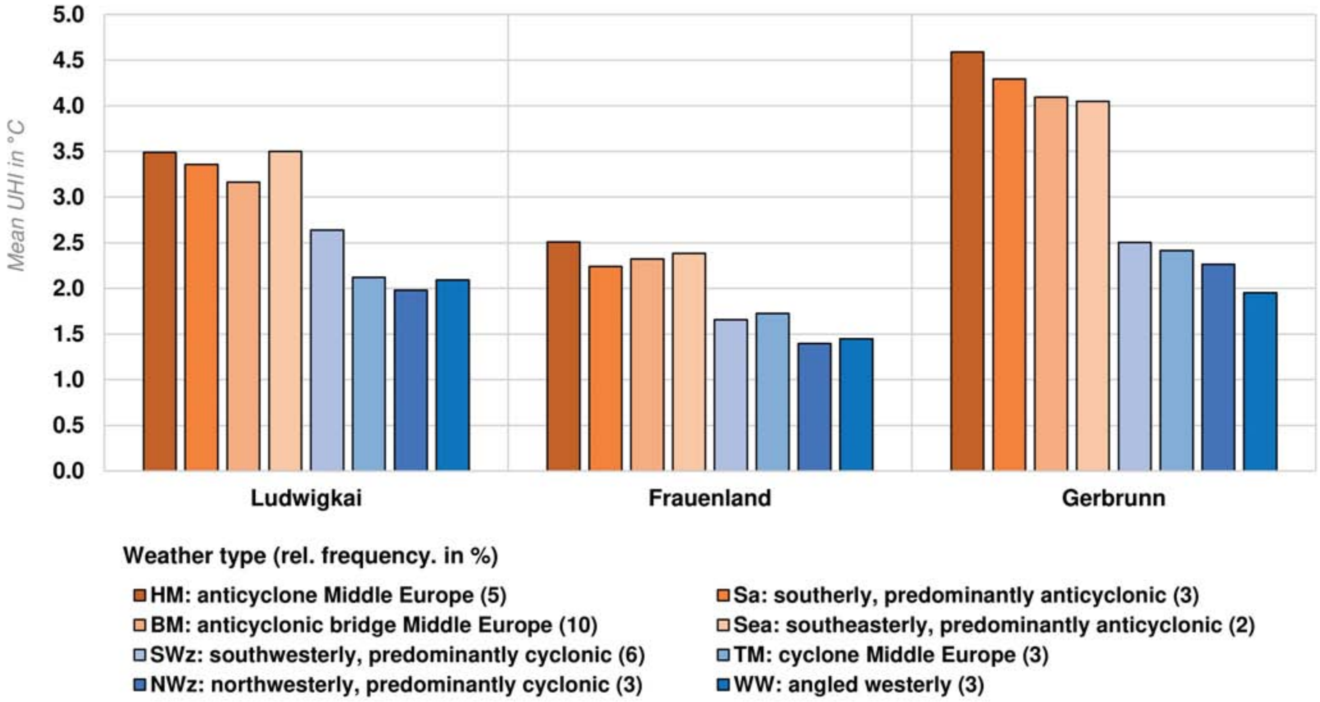

Figure 7: Maximum daily UHI effect between station Marktplatz and three suburban/rural stations as a function of daily weather types according to Hess and Brezowsky (1952), averaged over the 2018–2020 period. The numbers in brackets denote the relative frequency in % of the eight weather types that are related to the highest and lowest UHI effects, respectively.

situations over Central Europe favor the strength of the UHI in Würzburg. The UHI peaks when the anticyclone resides over Central Europe (weather type HM), prohibiting the horizontal and vertical mixing of air masses due to low wind speed and a near-surface temperature inversion (Xu et al., 2020). Cyclonic weather types do not inhibit the formation of the UHI, yet its amplitude is almost half as large as under anticyclonic influence. The impact of different weather types on the UHI is more visible, when the UHI is assessed between stations Marktplatz and Gerbrunn because the latter is characterized by an exposed location on a plateau outside the city and, hence, more prone to the large-scale circulation pattern.

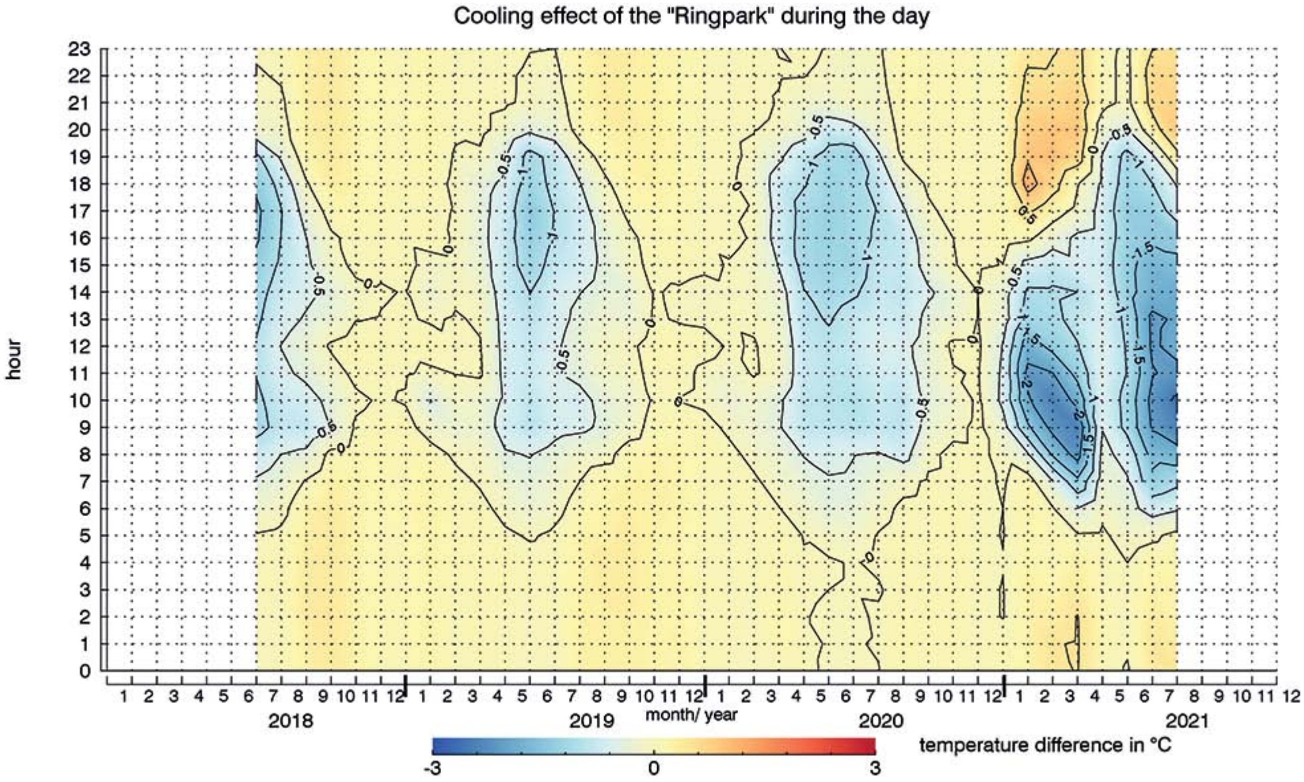

Figure 8: Same as Fig. 5 but for the cooling effect in °C by city trees (*Tilia cordata*) at station Ringpark.

3.4 Cooling effect of urban trees

In addition to the regular meteorological measurements at each station we also measured air temperature under the nearby canopies of narrow-leaved lime (*Tilia Cordata)* trees, apart from stations Marktplatz and Gerbrunn where no trees exist (see Fig. 1). Fig. 8 displays the isopleth diagram of the tree cooling effect at station Ringpark where the tree canopy is densest and, hence, the cooling effect is expected to be relatively high. The figure clearly reveals that the cooling effect of urban trees is confined to the warm season and to a time of the day that spans from noon until the late afternoon or even sunset. In winter and during night, the bio-physiological processes that produce the cooling effect, i.e., transpiration and shadowing, are not active because trees do not do photosynthesis and/or have no leaves. During the record-warm and dry years 2018–2020, the summertime cooling effect is virtually the same, amounting to more than 1 °C on average. In contrast, the more normal year 2021 has obviously enabled the city trees to mitigate the UHI more effectively by more than 2 °C, especially around noon, diminishing the UHI intensity to a great extent during this time of day. Less stress triggered by heat and drought and more abundant precipitation in 2021 has led to a higher vitality, more intense metabolism and denser canopy of the trees (Rahman et al., 2020, 2021).

Table 3 shows the mean cooling rate by city trees (always *Tilia Cordata*) at all stations across our meteorological network, along with the mean UHI with respect to station Marktplatz and the mean climate characteristics. The highly sealed station at 'Marktplatz' shows the highest values of air temperature and the lowest values of relative humidity. It is contrasted by colder and more humid conditions close to the river Main (Ludwigkai) and at both rural stations (Landesgartenschau, Gerbrunn). Not surprisingly the cooling rate peaks at station Ringpark where trees form a more or less closed canopy pattern. However, the cooling effect at the other five stations with tree population is still noticeable, ranging between 0.92 °C and 1.66 °C. Note that the full UHI effect of Würzburg is reflected by the rural stations in the bottom lines of Table 3, amounting to around 3 °C. Thus, city trees may mitigate between 33 % and 66 % of the total UHI, depending on location and growth conditions, but cannot completely compensate the enhanced thermal load in the city. Table 3 also points to another relevant aspect of urban heat stress, i.e., the mean cooling rate at sunset. It describes the temperature drop in the evening and is related to the recreational effect, e.g., after a heat day. Temperature decreases more strongly in the outskirts than in the inner city, although the temperature level before sunset is higher in the city compared to its surroundings. This fact can be seen best at the Altstadt-Dom station, which is located in the dense, highly sealed city core with the shape of an urban canyon. The canyon shape reduces the exchange of air masses. Thus, cooling in the evening is reduced, implying a longer heat exposure for city dwellers towards the evening, i.e., the time of the day when schoolchildren go to bed.

Table 3: Climatological characteristics, mean UHI effect and mean cooling rate by trees at the meteorological stations. The air temperatures are adjusted to the elevation level of the Markplatz by using the potential temperature. The UHI refers to the highest daily value in the daytime, the cooling at sunset denotes the difference between a time window before and after sunset, and the tree cooling rate is averaged over all daytime values at 10-minutes interval. Each indicator is averaged over all days during the 2018–2020 period.

Location	Mean air temperature	Mean rel. humidity	Mean highest UHI	Mean cooling at sunset	Mean tree cooling (tilia)
Ludwigkai	11,31	75,17	2,68	2,63	1,66
Marktplatz	12,09	70,2	0	2,06	no trees
Altstadt – Dom	11,99	70,93	0,37	1,89	1,08
Ringpark	11,62	74,53	2,04	2,62	2,17
Frauenland	11,59	73,41	2,01	2,29	1,03
Rottendorfer Tor	11,15	74,26	2,56	2,18	0,92
Landesgartenschau	10,81	74,99	2,93	2,35	1,35
Gerbrunn	11,04	75,64	3,32	2,78	no trees

Table 4: Surface temperatures measured during a special observing period on one of the most extreme heat days (30th of July 2018) at maximum solar altitude (1:20 p.m.), at two locations next to station Ringpark.

Side	In the sun	In the shadow
On an asphalt street	66.8 °C	37.2 °C
On a grassed area with trees	36.6 °C	27.5 °C

During one of the warmest weeks of summer 2018 a special measurement campaign was carried out, including several additional sites around station Ringpark. The most striking result is presented in Table 4, displaying the surface temperature in the early afternoon at four sites with different land cover and radiative conditions. The data was collected using a FLIR thermal imaging camera. These sites are less than 100 m apart from each other at a transition zone between inner city and park area. A tremendous local temperature contrast of more than 30 °C was observed between an open-sky site on an asphalt street and a nearby grassed area shadowed by several trees. These numbers highlight that the UHI is subject to a very heterogeneous micro-climatic pattern and, hence, a challenge for every monitoring system.

4 Discussion

Overall, the study period from 2018 to 2020 was characterized by anomalously warm and dry weather conditions. During winter this may have been triggered by a split of the polar vortex with different consequences: either the weather conditions become cold and dry (February and March 2018) or warm and moist (February 2020) (Butler et al., 2020; Greening and Hodgson, 2019). Persistent upper-tropospheric ridges with warm and anticyclonic weather conditions have been made responsible for the long-lasting positive temperature anomalies and dry spells, especially during the period from April to October 2018 and in summer 2019 (Hoy et al., 2020; Sousa et al., 2020). A stable Omega situation also caused the heat wave in August 2020 (DWD, 2020). The same atmospheric pattern implies subsidence and inhibits deep convection, leading to reduced rainfall and more dry days (Ahrens and Donald, 2015; Bott, 2012; Trapp, 2013). Especially in months with a strong negative precipitation anomaly we often registered more than 20 days without precipitation in Würzburg, which were typically interrupted by intensive but short and small-scale showers. This can also be seen by the interannual variability of the days without precipitation and explains their differences. (Rahman et al., 2020) demonstrated how such changes in rainfall distribution and heat events affect the heat fluxes and cooling effects of city trees in Würzburg. (Dirmeyer et al., 2021) also found out that there was a strong warming of the boundary layer, which allowed moisture to diffuse into the free atmosphere without condensation, desiccating the lower troposphere. The first part of our analysis has shown how these large-scale meteorological conditions in Central Europe affected the local climate in and around the city of Würzburg.

Another important issue to assess the urban climate of Würzburg pertains to the occurrence of climatological indicator days, as departures from the long-term climatology as well as along the urban gradient. The five times higher amount of heat days in the city of Würzburg reflects the impact of blocking weather conditions related to the upper-tropospheric ridge prevailing over Central Europe. For city dwellers this has induced enhanced heat stress and even severe risks for vulnerable people, especially when heat days occur together with tropical nights (Kemen and Kistemann, 2019). When several summer or hot days follow one after another in the form of a heat wave, this enhances the thermal heat load and implies dangerous health issues (Lozán et al., 2019b; Matzarakis et al., 2020). Several studies showed that there will be an increase of the frequency and intensity of heat waves and dry spells in Germany, particularly affecting urban agglomerations such as Würzburg (Schönbein et al., 2020; Früh et al., 2011; Paeth and Pollinger, 2019). This can be attributed to an increase of blocking weather situations, which is caused by a polar shift of the jet stream and a locking of planetary waves (Paeth and Pollinger, 2019; De Vries et al., 2013; Shepherd, 2014).

In addition to the anomalously warm summers, the 2018/2019 and 2019/2020 winters were very mild. In particular, the number of ice days was clearly below average. A distinct cold spell occurred in February/March 2018 that can be traced back to a sudden stratospheric warming (SSW) event with an accompanying split of the polar vortex, leading to the advection of cold arctic air masses to Germany (Greening and Hodgson, 2019; Butler et al., 2020). In 2019, the SSW event produced the opposite effect because our study region was located in the sector of warm air advection (Butler et al., 2020). (Monnin et al., 2021) assumed that the temporal location of the SSW event within the seasonal cycle determines its impact on the lower atmosphere. Indeed, the polar vortex was particularly pronounced in early 2020, leading to a strong jet stream as well as positive temperature and precipitation anomalies over Central Europe through the advection of mild and humid maritime air masses (Lawrence et al., 2020).

Altogether, these processes and boundary conditions serve as an explanation for the anomalously warm and dry period during 2018–2020 which, in turn, is important for the overall interpretation of our results. Indeed, the anomalies of temperature, precipitation and relative humidity observed in Würzburg during the 2018–2020 period resemble the future climatic situation around Würzburg that is simulated by an ensemble of several regional climate model projections from the EURO-CORDEX framework for the middle of the century, using the RCP 8.5 business-as-usual emission scenario (Schönbein et al., 2020). Thus, the characteristics of the UHI assessed during our anomalously warm and dry study period may foreshadow the ‘normal’ situation towards the middle of the 21st century, including heat stress and water shortage for citizens, especially in urban areas.

The UHI of Würzburg exhibits a distinct seasonal and diurnal cycle. Both cycles contribute to the problem of heat stress for the urban population: the UHI is most expressed during the warm seasons when heat days and heat waves prevail in Central Europe. This is given by the higher insolation linked to the high position of the sun during the summer. It encourages the heating of the sealed areas in the city and increases their heat dissipation around sunset. In interaction with high daily maximum temperatures and mild, or even tropical nights, sealed areas are getting warmer and warmer, because they are not able to cool down during the night. Especially heat waves can trigger positive feedback, which additionally reinforces this effect. In addition, the UHI peaks in the warm afternoon hours and, even more, towards the evening when people regenerate from a potential heat day and younger and older generations go to bed. This finding can be corroborated by other studies in partly different climate zones (Bueno et al., 2013; Baumüller, 2019). The UHI peak in the afternoon can be explained by the high position of the sun and the associated solar irradiation, favoring the radiation processes that largely contribute to the UHI generation. During summer 2019 this effect was more pronounced than in 2018 and 2020. This can be explained by the fact that, especially in June 2019, the weather situation was dominated by warm air advection and constant high pressure conditions with intensive solar irradiation (DWD, 2019). The evening peak of the UHI is related to the fact that during or shortly after sunset the heat flux of the heated, sealed surfaces in the urban area reaches its maximum, whereas the surrounding areas have already started cooling. This pattern was also found by other authors (Johnson, 1985; Hamdi and Schayes, 2008). Anticyclonic weather conditions favored an intense UHI peak in February 2019 and 2021. In both of these years, an exceptionally high sunshine duration along with warm air masses has been observed by the German Weather Service (DWD, 2019a, 2021c). This situation boosted the UHI as the sealed areas could heat up during the day and cool down quickly due to the outgoing radiation. Because the warm weather phase was preceded by a cool period, the effects were slightly muted on average. However, the city of Würzburg clearly stands out due to the remarkable amplitudes of the UHI which partly exceed 8 °C in a city with about 130,000 inhabitants. The reduction of the UHI during the night does not take place linearly but in several stages, probably due to an episodic entry of fresh air that breaks through the urban boundary layer. If the inflow is interrupted, the air masses can be warmed up again, briefly strengthening the UHI effect. A similar mechanism was noted by (Clay and Guan, 2020) in connection with the cooling effect of urban park areas. This process is active until sunrise, when a stronger warming of the outskirts takes place due to the missing shadow of buildings (Johnson, 1985; Hamdi and Schayes, 2008) and to the different heat capacities (Haeger-Eugensson and Holmer, 1999).

The UHI intensity also depends on the daily maximum temperature and on the prevailing weather type: if maximum temperature lies between 15 °C and 25 °C, an expected UHI level is observed, according to the formula of Oke (1973). If the daily maximum temperature exceeds 30 °C or even 35 °C, the UHI effect exceeds the expected maximum value of 6.2 °C. Fig. 6 has revealed a statistically significant correlation between the daily maximum temperature and the UHI of Würzburg. This can be explained by the fact that higher daily maximum temperatures and higher UHI levels are linked to the same atmospheric circulation patterns, especially during the warm seasons. This mainly pertains to anticyclonic weather patterns and locations on the front side of a trough with enhanced solar irradiation and warm air advection, whereas cyclonic situations with cloudy and rainy weather weaken the UHI of cities in Central Europe by mixing of the near surface layers (Hardin et al., 2018). In the present study, this could be confirmed for the city of Würzburg: the UHI is more expressed under anticyclonic weather conditions that impede the horizontal and vertical mixing of air masses due to reduced wind speed and a lower-tropospheric inversion (Xu et al., 2020). Cyclonic weather types cannot inhibit the formation of the UHI but provoke a much smaller temperature gradient between inner city and outskirts. Thus, the occurrence of indicator days (heat/frost days and tropical nights) assessed during our anomalously warm and dry study period may foreshadow the 'normal' situation towards the middle of the 21^{st} century. It can be expected that during such periods in boreal summer, the UHI of Würzburg will be particularly expressed, leading to heat stress and water shortage for urban citizens and urban green. Overall, we see a clear link between the weather type and the strength of the UHI. It is well known that a high solar radiation leads to a strong heat island effect (Ahrens and Donald, 2015; Lozán et al., 2019b). High pressure is often accompanied by a high solar radiation. Due to the location of the highs in nearly stationary Rossby waves or in the form of an upper ridge, these weather conditions were very persistent during the study period from 2018–2020. It is assumed that such conditions of high pressure are lasting longer as the disproportionate warming of the Arctic leads to a weakening of the polar front jet. As a result, the high geopotential is dissolved more slowly (Paeth and Pollinger, 2019; Zschenderlein et al., 2019). When a stable ridge establishes over middle Europe in the northern hemisphere summer, the interaction of warm air masses and a high solar radiation can favor a high heat stress for dwellers, which can be further intensified by the UHI. Depending on the season and other influences, such as the SSW events, different effects on the urban heat island can arise. The effects of the SSW events in early spring 2018 and in 2019 should be mentioned here as an example.

The measurements under the tree canopy have demonstrated that city trees in Würzburg have a noticeable cooling effect on near-surface air temperature. The cooling effect is largest when solar irradiation peaks during the diurnal and seasonal cycles and emanates from plant-physiological processes such as transpiration and photosynthetic activity as well as physical effects such as interception and shadowing (Rahman et al., 2020; Pretzsch et al., 2021; Moser et al., 2015). Especially on hot days, city trees can provide a significant cooling effect (Rahman et al., 2021). It was found that there is a higher cooling effect of city trees if they are planted in larger groups, like in park or alley formations. In the present study, a cooling effect could also be measured in densely built areas like Altstadt-Dom. The low cooling effect of the trees at station Rottendorfer Tor can be explained by a pronounced easterly wind that often forms along a fresh air corridor, drifting downhill into the city. (Rahman et al., 2020) were able to manifest the importance of city trees in Würzburg and determined cooling effects of up to 11 PET. During night, the temperatures under the tree canopy adjust to the values in the surrounding area due to the missing solar radiation and photosynthetic activity. City trees in public places, along streets, squares and footpaths can achieve a more comfortable climate for the inhabitants and, hence, represent a suitable adaption strategy for cities and municipalities in times of climate change with an increasing tendency towards hot days and heat waves. However, it is important that the needs of the plants are adhered to, e.g. through an adapted water management (Rahman et al., 2020; Böll, 2014). Indeed, our study revealed that the cooling capacity of city trees was more than twice as large in the first half of 2021 when the trees did not suffer from heat and water stress, in contrast to the years 2018–2020. This imposes a challenge to the management of green infrastructure in the city of Würzburg, since recent studies on regional climate change have pointed to the current and future threats for trees and crops in northern Bavaria (e.g. (Ziegler et al., 2020; Kapsch, 2022)).

Water bodies such as the Main river have also a notable effect on the urban climate. Station Ludwigkai is characterized by a lower UHI effect, less warm days and a stronger cooling rate at sunset, despite this area is adjacent to the inner city. The reason is a Bowen ratio with lower sensible and enhanced latent heat fluxes due to evaporation from the water surface (Park et al., 2019). In contrast to the rural stations, we find a slightly higher number of tropical nights at the riverside station of Ludwigkai. This underlines the findings from previous studies such as (Yang et al., 2018). But the cooling effects of the water body during the day outweighs the minor disadvantages on nighttime cooling. The same phenomenon can be observed in the park area at station Ringpark, but here enhanced transpiration and interception from the tree canopy are responsible for the cooling effect (Rahman et al., 2017). In summary, our results suggest a better management of blue and green infrastructure to mitigate the heat stress in Würzburg.

5 Conclusions and outlook

The assessment of the urban climate of Würzburg during the years 2018–2020 coincided with an anomalously warm and dry period in Central Europe. This is reflected by an above-average number of summer days, hot days and tropical nights compared with the long-term mean climate. In addition, they occurred more frequently in the city center than in the outskirts. Besides heat stress, especially for city dwellers, water shortage prevailed during this period. Monthly precipitation was often below 40 % of the normal amount, interrupted by only a few months with positive anomalies. In total, the region around Würzburg misses a complete annual precipitation sum since 2015 (Paeth et al., in review). The overall dry weather conditions also led to continuously negative anomalies of relative humidity in Würzburg, especially during the warm season.

Due to the high building density, the prevailing building materials and the low extent of green spaces, the urban built up areas of Würzburg warm up substantially during the day compared with the outskirts. This is particularly noticeable during the evening hours in the form of an UHI-effect of partly more than 8 °C. This is clearly more than would be expected from the number of inhabitants and is due to the topographic situation in a steep valley and the low ratio of green to sealed areas. The UHI of Würzburg exhibits a clear seasonal and diurnal cycle: maxima occur in the afternoon and, even more, during the evening hours, especially during the summer months. The UHI mostly levels out in the morning before sunrise and builds up again during the course of the day. A statistically significant correlation was found between the daily maximum temperatures and the associated UHI effect. Anticyclonic weather types enhance the UHI effect while cyclonic activity is linked to a stronger horizontal and vertical mixing of air masses.

The seasonal and diurnal occurrence of the UHI, especially when the temperatures rise over the mark of a summer or heat day, triggers the problem of heat stress in the city of Würzburg because maxima prevail during the warm season when heat waves become more and more apparent in Central Europe (Paeth et al., in review; Paeth and Pollinger, 2019) and during the evening hours which typically serve as a recovery time for the urban population, e.g. after a heat day. City trees and open water bodies can make an efficient contribution to reduce the temperature level in public open spaces, especially in the afternoon, and thus increase the thermal comfort for people. In order to ensure a high cooling efficiency, it is important that the trees are planted according to their species-specific preference (Rahman et al., 2020; Rötzer et al., 2021). This can also be transferred to other cities of the world.

The continuous monitoring of the urban climate of Würzburg enabled an in-depth analysis of climatic gradients at different spatial scales and their variations during the seasonal and diurnal cycle as well as under various large-scale weather conditions. Thus, one novelty of our study pertains to this comprehensive assessment over more than three years along an extended urban gradient, allowing for a detailed spatiotemporal quantification of the UHI and revealing a high exposure of urban dwellers and city trees to heat and water stress. Another peculiarity of this analysis is given by the fact that our urban climate monitoring coincided with a record-warm and dry period, especially in summer, when the UHI is most expressed. Thus, the results presented here can be seen as the local urban footprint of a warmer Central European climate as it is expected to develop under the course of future climate change (Früh et al., 2011; Paeth et al., in review). A third novel aspect relates to the accompanying measurements under the tree canopy that allowed for an unprecedented quantification of the cooling effect by city trees under different local conditions.

Future work is intended to be carried out along three research lines: (1) the meteorological measurements in Würzburg are intended to be perpetuated, including additional low-cost sensor boxes. (2) The relationship between larger-scale atmospheric flow patterns and the local UHI of Würzburg will be quantified by means of statistical models that can be applied to weather type statistics under present-day and future climatic conditions. Indeed, several modeling studies point to more frequent anticyclonic patterns in summer over Central Europe when greenhouse gases continue to increase (e.g., Paeth and Pollinger, 2019). They may lead to more frequent heat waves and dry spells in the climate hotspot region of Lower Franconia (Paeth et al., in review). (3) We aim at the spatial extrapolation of our assessments by means of the large eddy-based urban climate model PALM-4U. This very high-resolution model can also be used to simulate the effect of new building structures and of improved management strategies for the green and blue infrastructure in Würzburg.

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