Air temperature characteristics of local climate zones in the Augsburg urban area (Bavaria, southern Germany) under varying synoptic conditions

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ABSTRACT

In this contribution air temperature differences among Local Climate Zone (LCZ) categories are analysed with special consideration of varying synoptic conditions. Analyses are based upon an LCZ mapping for the urban area of Augsburg (Bavaria, Southern Germany) and hourly air temperature data from a comprehensive logger network. Quality checked air temperature measurements have been stratified according to season, hour of the day and weather situation. For resulting subsamples thermal differences among LCZs have been determined and appropriate statistical tests have been applied. Results confirm that built up LCZs feature higher temperatures than natural LCZs and that most distinct differences among LCZs appear under undisturbed synoptic conditions. With increasing cloudiness and in particular with increasing wind speed differences among LCZs diminish. But, even for strongly disturbed synoptic conditions statistical significance of the influence of LCZs on thermal characteristics could be assured. Thus, our findings provide clear evidence that detectable thermal differences among LCZs are not restricted to „ideal "synoptic conditions but occur as well under disturbed conditions. However, to assure not only the statistical but also the climatological and in particular the bioclimatological and human health related relevance of the documented differences among LCZs further studies incorporating appropriate metrics are intended.

1. Introduction

The climate characteristics of urbanized areas differ distinctly from those observed in their rural and natural surroundings. These urban climate modifications comprise urban-rural differences in various climate parameters, with the so called urban heat island (UHI) being the most prominent phenomenon illustrating the warming effect of urban structures on air temperature (Oke, 1987). Beside climatic differences between urban areas and their surroundings distinct differences also exist within the urban environment. Both effects –urban-rural and intra-urban climatic differences – are due to the spatial distribution of specific features (e.g. natural surfaces, sealed surfaces, buildings) that impact atmospheric processes and thus lead to distinct local scale climate modifications.

A recent approach to objectively categorize urban and rural structures with respect to their specific influences on local climate

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characteristics is the so called “local climate zone” (LCZ) concept that has been introduced by Stewart and Oke (2012). Primarily the LCZ concept intends to support the comparable and consistent selection and documentation of representative measurement sites and thus to enable the standardized determination of urban-rural and intra-urban climatic differences (as differences between pairs of specific LCZ categories) that are comparable among different urban regions (Stewart et al., 2014).

However, beside these main applications the LCZ concept has been applied to determine spatial patterns of climate relevant urban and rural structures for cities and their surroundings worldwide. Mainly in the framework of the World Urban Database and Access Portal Tools (WUDAPT) project (Mills et al. 2015) LCZ classifications and maps have been produced for numerous cities around the world following a standardized workflow (Bechtel et al., 2015). Based on these standardized informations on surface structure and surface cover it is possible to assess spatial patterns of potential local scale climate characteristics for individual urban areas and moreover to compare urban areas on the basis of consistent and objective criteria.

Accompanying the LCZ mappings the thermal characteristics of the LCZ categories have been analysed for different cities and utilizing different observational air temperature data sets.

Siu and Hart (2013) analysed thermal LCZ characteristics in the urban area of Hong Kong (SAR, China) on the basis of 17 meteorological measurement sites. Lehnert et al. (2015) compared temperature characteristics of LCZ categories in Olomouc (Czech Republic) using air temperature data from 14 measurement sites. Alexander and Mills (2014) utilized data from 6 fixed stations and from additional mobile measurements to examine LCZ specific air temperatures in Dublin (Ireland). Stewart et al. (2014) investigated LCZ climates – mainly on the basis of mobile measurements – in Nagano (Japan), Vancouver (Canada) and Uppsala (Sweden). For Nancy (France) Leconte et al. (2015) also performed mobile air temperature measurements to evaluate air temperature characteristics of LCZ types. For Berlin (Germany) Fenner et al. (2014, 2017) analysed LCZ specific temperature characteristics on the basis of up to 19 fixed meteorological stations and additional around 400 citizen weather stations. Several investigations of the air temperature characteristics of LCZ categories have been conducted in Szeged (Hungary) by Gál et al. (2016) using data from 24 fixed measuring stations, by Skarbit et al. (2017) analysing data from a subset of 20 selected stations and by Unger et al. (2017) performing analyses focusing on human bioclimatological aspects using data from six selected stations.

In general, results from these studies confirm the thermal relevance of the LCZ categories and thus the climatological validity of the LCZ concept for urban areas of varying size, with different urban structural settings and exhibiting different macro- and meso-climatic boundary conditions. In particular, distinct thermal differences have been ascertained between structurally diverse LCZ types – e.g. densely built-up surfaces versus open-space configurations – and for ideal - calm and clear - synoptic conditions. To the authors' best knowledge, no studies so far have explicitly investigated in how far thermal characteristics of LCZ types behave under varying synoptic boundary conditions. Investigations in this direction are important in order to determine the order of urban-rural and intra-urban temperature differences that are related to different magnitudes of synoptic perturbations of the ideal i.e. calm and clear conditions. Although less pronounced than during ideal conditions spatial temperature variations accompanying disturbed conditions may nevertheless be significant and may have relevance considering human health related aspects.

Against the scientific background as briefly outlined above, the objectives of the analyses presented in this contribution are defined as follows:

- Based on automatically derived local climate zones for the urban area of Augsburg meteorological measurement sites are assigned to LCZ categories.
- Utilizing hourly mean air temperature data from suitable stations thermal characteristics of the LCZ types are determined and expressed as deviations from a reference station.
- LCZ specific air temperatures are investigated considering inter- and intra-zone variations and taking into account temporal (season, time of the day) differences and as well variations related to varying synoptic boundary conditions (i.e. categories of wind speed and cloud cover at a reference station), thus contributing to the climatological evaluation of the LCZ scheme.

Accordingly, the paper is structured as follows: Section 2 introduces the data sets underlying our analyses and explains the different methodological approaches that have been applied. In Section 3 the main results are presented and illustrated. Finally, Section 4 discusses our findings and provides some essential conclusions and a brief outlook.

2. Data and methods

2.1. Study area

Our study area is the urban area of Augsburg in Bavaria, Southern Germany. The area comprises the city of Augsburg (288.631 inhabitants, 146.86 km^2; Stadt Augsburg, 2017) and the surrounding municipalities of Stadtbergen, Gersthofen, Friedberg and Königsbrunn (Fig. 1). The long-term (1981–2010) mean annual air temperature in Augsburg is 8.5 °C, the warmest month is July (18.1 °C), the coldest month is January (−0.8 °C), the mean annual rainfall is 767 mm (Fig. 2; DWD, 2018a). The main wind direction is southwest and the mean wind speed is 2.9 m/s (DWD, 2018b).

2.2. Local climate zone classification for the urban area of Augsburg

The LCZ concept as introduced by Stewart and Oke (2012) discriminates ten built-up LCZ types and seven natural LCZ types (see Stewart and Oke, 2012 for a comprehensive description). Each of these LCZ types is characterized by a particular combination of

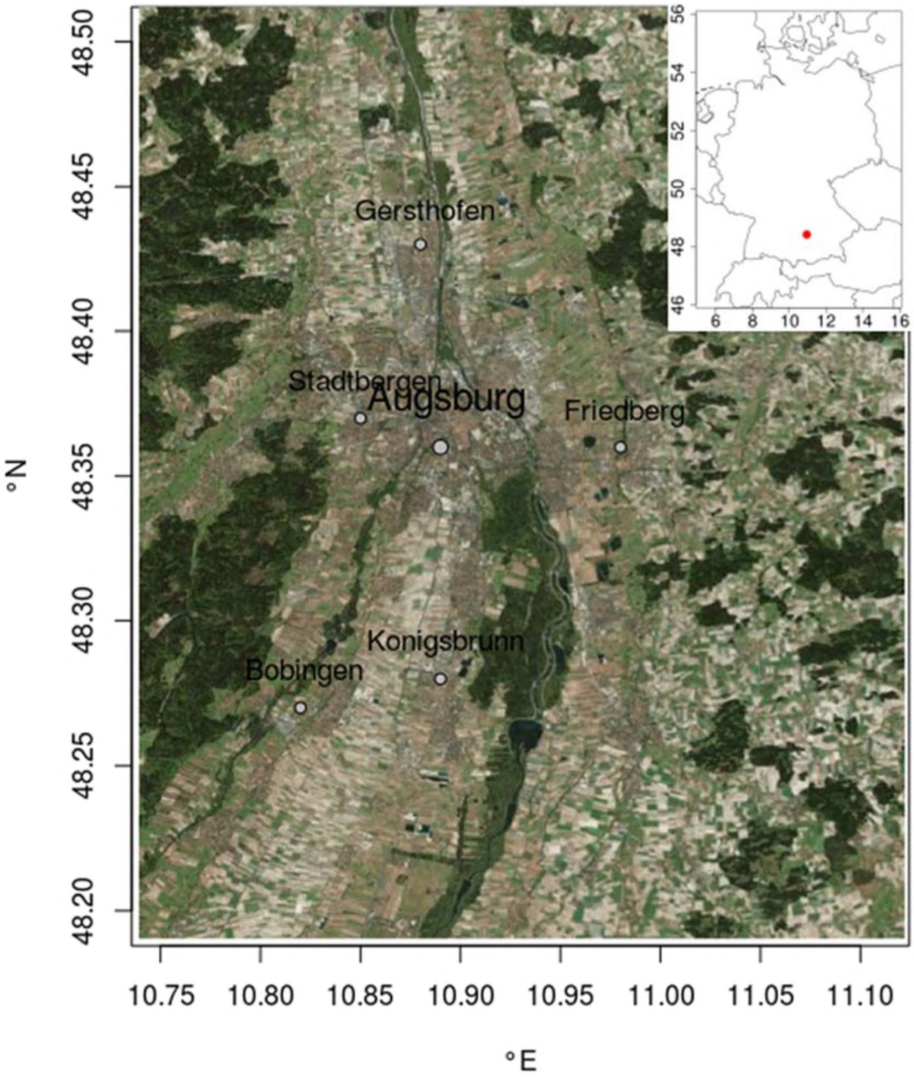

Fig. 1. Satellite map of the urban area of Augsburg. The location of Augsburg in Germany is indicated with the red dot in the inset map in the top right. (© Imagery: Bing Areal). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

surface structural parameters, e.g. sky view factor, building surface fraction, pervious/impervious surface fraction and height of roughness elements.

LCZ types for the urban area of Augsburg have been determined following the standardized "WUDAPT-workflow" (Bechtel and Daneke, 2012; Bechtel et al., 2015).

The main steps of this approach are (1) the determination of so called "training areas" (TA) that are intended to represent prototypical surface structure configurations for the respective LCZs, (2) the utilization of the specific spectral properties of these TAs to classify each pixel of selected Landsat scenes by a random forest algorithm implemented in the SAGA open source GIS software (Conrad et al., 2015). The included Landsat scenes (LC81940262014072LGN00, LC81940262014088LGN00, LC81940262014200LGN00, LC81940262015155LGN00, LC81940262015203LGN00, LC81940262015219LGN00) are from six dates in the years 2014 and 2015 between mid of March and beginning of August.

For the urban area of Augsburg four urban or built-up and five natural LCZ types have been determined for 100 m × 100 m raster cells as displayed in Fig. 3. The relative frequencies of LCZ types appearing in the study area are given in Fig. 4.

The most frequent urban LCZ type in the study area is Open Low Rise covering about 19% of the study area mainly in the suburban areas and often adjacent to LCZ type Large Low Rise extending over ca. 7%. The most intensely built up LCZ types Compact Mid Rise (ca. 1%) and Open Mid Rise (ca. 11%) appear mainly in the city centre of Augsburg; in particular Compact Mid Rise being mainly restricted to the most central parts. Among the natural LCZ categories the Low Plants class reaches highest percentages (41%) and is present mainly in the southwest, northwest and northeast of the study area. The forested LCZ types Dense Trees and Scattered

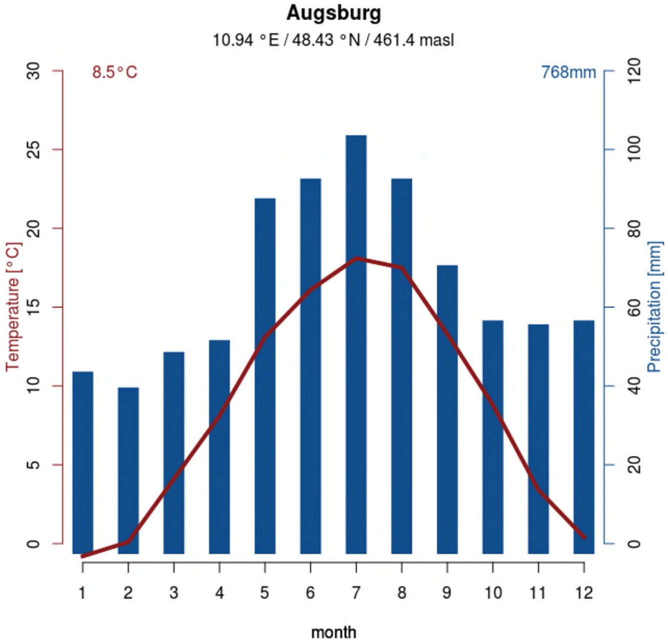

Fig. 2. Climate diagram for the station Augsburg-Mühlhausen for the period 1981–2010. Red line: mean monthly air temperature, blue bars: mean monthly precipitation sums; respective long-term mean annual values are given in the top left and top right respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

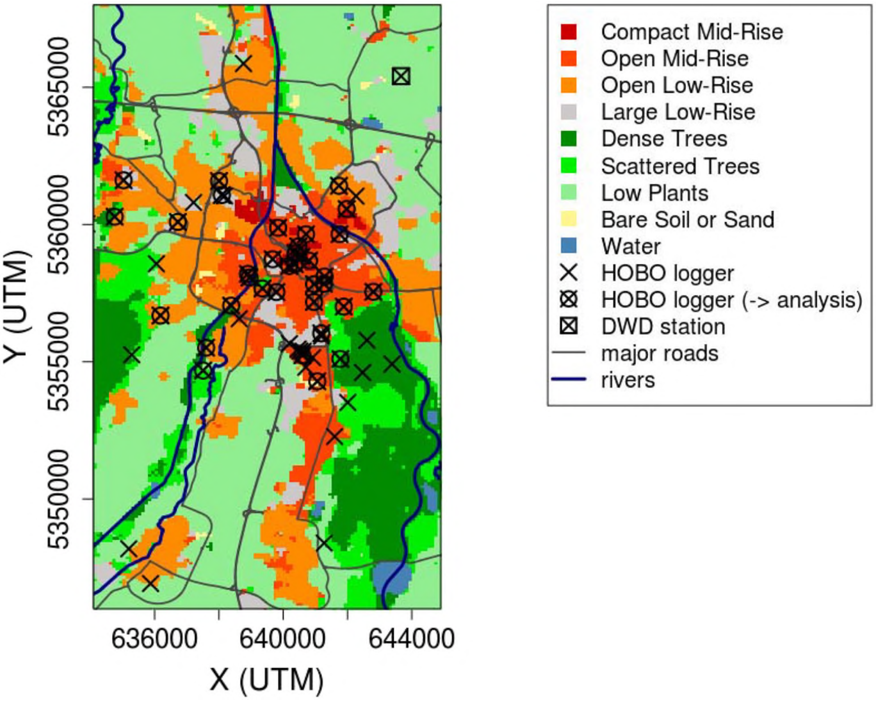

Fig. 3. Spatial distribution of Local Climate Zone (LCZ) types in the urban area of Augsburg. Symbols indicate sites of the urban meteorological network (HOBO-Logger) and the location of the meteorological reference station (DWD-Station). HOBO logger sites that are included in further statistical analyses are indicated with a circle/cross signature.

Trees together are summing up to around 20% of coverage and appear mainly along the Lech and Wertach River that are running from the southeast and the southwest respectively to the north of the study area. The largest area covered by Dense Trees and Scattered Trees is the so called Augsburger Stadtwald to the southeast of the city and to the west of the Lech river.

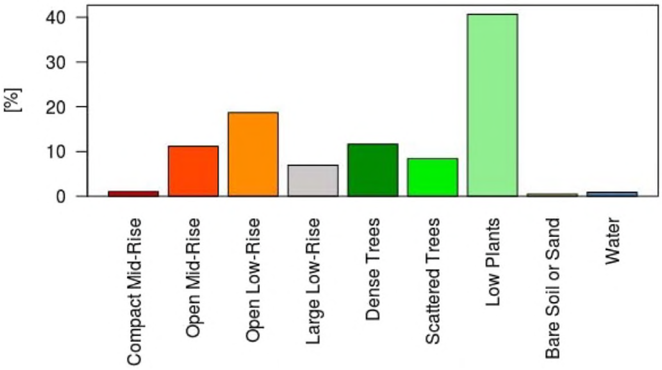

Fig. 4. Percentages (%) of land area covered by different Local Climate Zone (LCZ) types in the study area depicted in Fig. 3.

The LCZ categories Water and Bare Soil or Sand are represented with only marginal percentages (0.5% and 0.9%) with Bare Soil or Sand appearing only in fragmented small areas and noteworthy Water areas being mainly restricted to small lakes accompanying the Lech river in the southeastern part of the domain.

2.3. *Urban meteorological network*

A meteorological network in the urban area of Augsburg and its rural surroundings has been set up in 2012 in a cooperative effort of the Helmholtz Zentrum München (German Research Center for Environmental Health, Institute of Epidemiology, Environmental Risks) and the Universität Augsburg (Institute of Geography, Physical Geography and Quantitative Methods). Measurements of air temperature and relative humidity are conducted with 4 min temporal resolution since December 2012 with ONSET HOBO Pro v2 loggers U23–001 (Onset, 2010). The loggers' accuracy for air temperature measurements is ± 0.21 °C from 0 to 50 °C and the respective resolution is 0.02 °C at 25 °C according to the manufacturer (Onset, 2010). The loggers are not ventilated but are all provided with a solar radiation shield. Due to practical and security reasons not all loggers could be mounted at the standard measurement height of 2 m above the ground. However, all loggers are located between approximately 1,5 m and 2,3 m above ground.

Air temperature and relative humidity data are available for 80 logger sites. Locations of loggers inside the study area are displayed in Fig. 3 and their temporal data availability is indicated in Fig. 5. As can be seen from Fig. 5 data availability differs distinctly among sites due to rearrangements of the network (e.g. in the context of short-term epidemiological measurement campaigns) and necessary relocations of loggers (e.g. due to construction works at individual sites). However, quasi continuous observations are available for about 40 sites since around May 2014.

2.3.1. *Quality control of the temperature data*

A thorough quality control procedure has been applied to the air temperature data from the logger network including a fixed range test (e.g. Estévez et al., 2011), tests for temporal as well as spatial outliers (e.g. Gandin, 1988), a persistence test (e.g. Estévez et al., 2011) and a step test (e.g. Shafer et al., 2000).

In order to define a realistic fixed temperature range, the long-term range of hourly air temperature measurements at the suburban/rural station from the German Meteorological Service (DWD) at Augsburg-Mühlhausen (DWD, 2018c) has been taken into account. As sub-hourly air temperature measurements in an urban environment may exceed positive temperature extremes at a suburban/rural reference station the temperature range estimated from the Augsburg-Mühlhausen station has been extended accordingly. Thus, air temperatures from the logger network outside the range from −30 °C to 45 °C have been regarded as unrealistic and have been omitted from any further tests and from any further data aggregation and analyses.

All further quality assessments result in the assignment of quality flags for each observation.

Temporal outliers have been defined using site-specific 3-monthly running quartiles. Values outside the range median ± x* interquartile range have been marked as potential temporal outliers. In order to determine the most adequate value of the multiplication factor *x* a procedure used by Eischeid et al. (1995) has been applied. To this end the percentage of observations flagged as outliers has been calculated for varying values of the multiplication factor *x* (Fig. 6). According to Eischeid et al. (1995), the threshold value for flagging temporal outliers has been determined as the value of *x* for which the slope of the curve in Fig. 6 is getting close to zero. This results in $x = 2.75$, which appears to be reasonable, as according to Vellum and Hoaglin (1981) a typical value for the multiplication factor *x* is 3 when a fixed value is used. However, a temporal outlier of the same sign occurring at another site in the network within a period of ± 4 min around a particular time step can confirm temperature values preliminary marked as temporal outliers.

Suspicious persistent temperature values have been determined using a moving window of one hour of observations, which corresponds to 15 consecutive 4-minute values. Temperature values persisting over a one hour period have been flagged as erroneous unless this persistence is confirmed by observations at other stations within the network.

In the step test unrealistic temperature changes have been determined as differences between two consecutive time steps

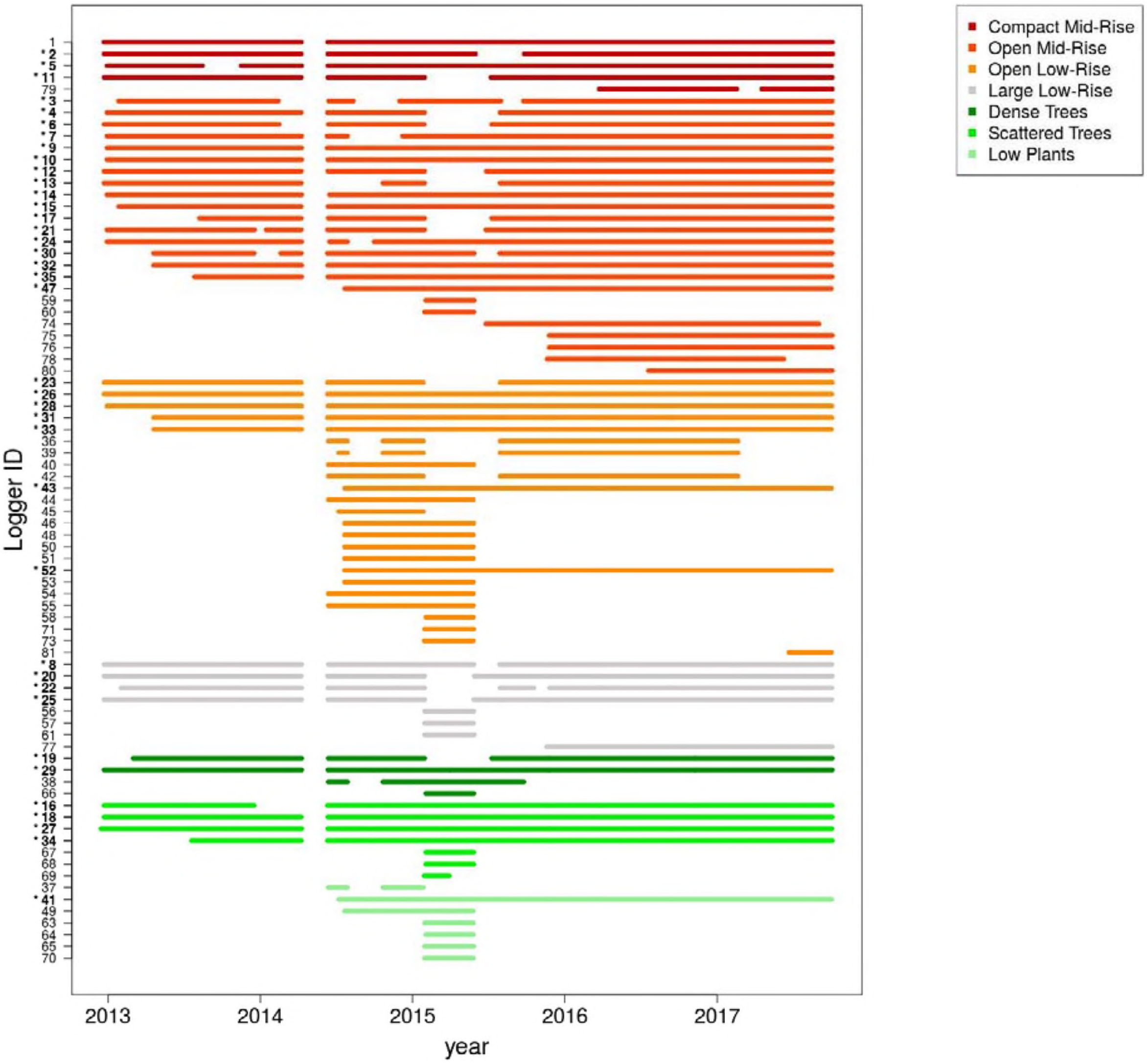

Fig. 5. Temporal availability of measurements at 80 logger locations of the meteorological network in the urban area of Augsburg. Colours indicate the affiliation of logger sites to LCZ categories. Locations selected for further analyses are marked with stars.

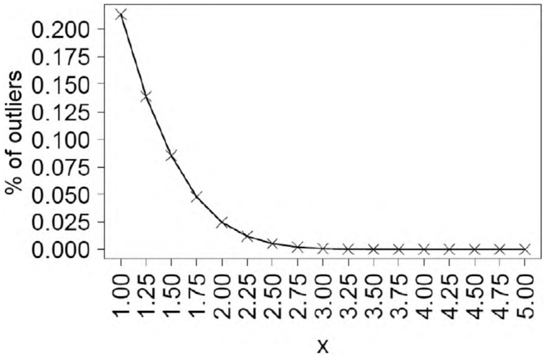

Fig. 6. Percentage of detected temporal outliers utilizing varying values of the multiplication factor x.

exceeding a threshold value of 5 °C. If not confirmed by another station within the network such values have been flagged as erroneous. Besides, a test for persistence on a higher or lower temperature level after an unrealistic temperature change has been carried out by examining the differences within the whole network at the time steps after the unrealistic change.

Table 1

Quality flags assigned to 4-min air temperature data from the urban meteorological HOBO logger network.

Quality flags	Number of observations	% (of available observations)
(0) No flag (passed all tests)	24,575,414	96.0991
(1) Flagged but confirmed by another station	448,638	1.7543
(2) Failed fixed range test	21,984	0.0903
(3) Failed temporal outlier test	17,693	0.0692
(4) Failed persistent values test	54,281	0.2123
(5) Failed step test	688	0.0027
(6) Failed persistence after step test	837	0.0033
(7) Failed spatial outlier test	376,558	1.4725
Flagged by more than one test	312,835	1.2233

Finally, in order to test for spatial consistency reference time series have been calculated for each station using an inverse distance weighting approach with the Pearson correlation coefficient among sites utilized as distance measure. Hereby, corresponding air temperature measurements from those six logger stations reaching highest positive correlations with a particular site have been taken into account. Once a reference time series has been calculated, the next step has been the calculation of the standard deviation of the temperature observations within a time window of ± 4 min around the given time step for the whole network. If the difference between temperature measurement and reference value exceeds twice the standard deviation within the network, these values were regarded as spatial outliers, but again could be confirmed by observations exhibiting corresponding anomalies. For time steps having less than six corresponding observations from neighbouring stations, the spatial reference value was not calculated. Instead, the test for spatial consistency utilized 3-monthly running mean values and standard deviations for each station. Observed values outside the range mean ± 2* standard deviation were then considered as spatial outliers.

An overview on the results of the quality control procedure is provided in Table 1. Overall, almost 98% of the 4-min air temperature measurements passed all quality checks (Flag 0) or have been confirmed by corresponding measurements (Flag 1) and thus can be assumed to be reliable. For all subsequent analyses, hourly mean air temperatures have been calculated utilizing only those observations that have not been flagged erroneous concerning any of the above detailed tests (Flag 0) or have been confirmed by comparison with corresponding data (Flag 1).

2.4. Assignment of logger sites to LCZ types

The HOBO logger sites have been assigned to LCZ categories based on the LCZ classification briefly described in section 2.2. Thereby, logger sites have been allocated to the LCZ type of the respective appropriate 100 m × 100 m LCZ raster. However, additionally the LCZ coverage of the adjacent rasters and also local expert knowledge of site specific surface structural characteristics have been taken into account.

From all available logger sites only those have been selected for further investigations that (1) could have been unambiguously assigned to an LCZ category and (2) dispose of temperature data for a sufficiently long period to enable comprehensive comparative analyses of thermal LCZ characteristics. The finally elected 38 logger stations are marked in Figs. 3 and Fig. 5 and are distributed among LCZ categories as follows.

To the built up LCZs Compact Mid Rise, Open Mid Rise, Open Low Rise and Large Low Rise 3, 17, 7 and 4 logger sites are assigned respectively. The natural categories Dense Trees, Scattered Trees and Low Plants are represented by 2, 4 and 1 loggers respectively. No logger sites are situated within the only marginally occurring LCZ categories Water and Bare Soil or Sand.

From the temperature data available for the selected sites only those cases have been used for further analyses for which hourly data from all selected logger sites are available. Fig. 7 illustrates the temperature variations (hourly means) at the 38 selected logger sites for all time steps with 100% data availability among the selected sites. As can be seen from Fig. 7 the data availability covers the period from end of 2014 (2014/12/15) to late 2017 (2017/10/05), however, with extensive periods of incomplete data coverage especially in 2015. Hourly mean air temperatures in the urban area of Augsburg during this period are in the range of approximately −18 °C and 36 °C; the mean over all valid hourly mean values is ca. 8.3 °C. Mean values derived for the different LCZs via averaging over all logger sites assigned to the respective LCZ type are illustrated in Fig.7 as well.

2.5. Meteorological reference data and definition of synoptic categories

For our analyses of the thermal variations within and among LCZ types in the Augsburg urban area we compare the hourly mean HOBO logger data to hourly meteorological observational data gathered at the official station of the German Meteorological Service (DWD) at Augsburg-Mühlhausen (DWD, 2018c; see Fig. 1 for the location of the station) that is located in LCZ type Low Plants.

Furthermore, certain combinations of wind speed (in m/s) and cloudiness (in oktas) measured at Augsburg-Mühlhausen have been utilized to define synoptic categories for the weather-related stratification of the LCZ related thermal properties.

Several approaches exist for the delineation of synoptic boundary conditions that are advantegous or disadvantageous for the development of specific urban climate characteristics in particular the urban heat island effect. For demarcating ideal weather conditions that allow for nocturnal cooling and thus enable the emergence of an UHI the so called weather factor (Oke, 1998) that

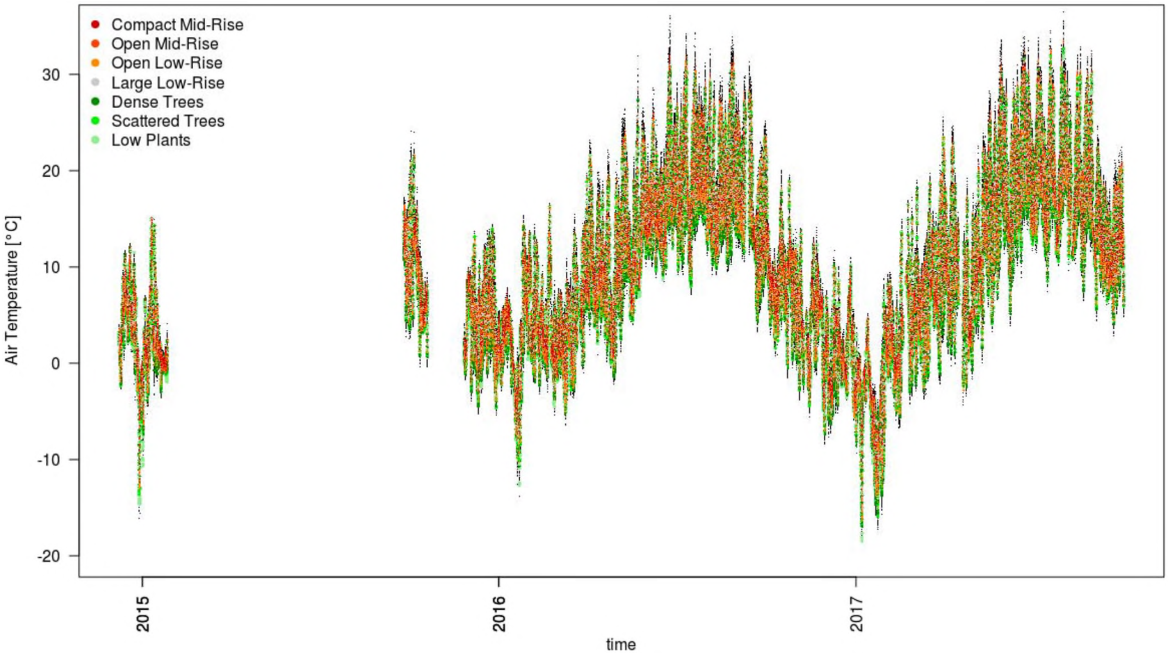

Fig. 7. Hourly mean air temperatures (in °C) at all 38 selected logger sites from the Augsburg urban meteorological network (black solid circles) and hourly air temperatures averaged for LCZ categories (coloured solid circles).

relates the UHI magnitude to cloudiness and wind speed has been utilized by several authors (e.g. Gál et al., 2016; Stewart et al., 2014). Other approaches towards a quantification of the dependency of the UHI on wind speed and cloudiness are also available from Böhm and Abl (1978) or from Morris et al. (2001).

For our analyses we defined 16 synoptic/weather categories based on hourly values of wind speed and cloud cover at Augsburg-Mühlhausen utilizing as threshold values multiples of 2 m/s and 2 octas respectively. The resulting categories together with their respective sample sizes (number of hourly observations) are displayed in Table 2. From Table 2 it is obvious that the available observations are far from being evenly distributed over the different synoptic categories. This has to be taken into account when applying subsequent statistical analyses and when interpreting respective results.

2.6. Statistical data analyses

In order to derive quantitative estimates of intra- and inter-LCZ variations in thermal characteristics the available hourly mean air temperature data have been grouped according to LCZ categories, time of the day, season and synoptic/weather situation.

As – in the overwhelming number of cases - normal distribution of the analysed samples cannot be assumed nonparametric statistical analyses have been applied to ascertain statistical significance of thermal differences among LCZ categories. For testing the null hypothesis that the mean ranks of all LCZ categories are the same the Kruskal-Wallis test (Kruskal and Wallis, 1952) has been applied. In addition, pairwise Wilcoxon rank sum tests (Wilcoxon, 1945) including the Holm adjustment of *p*-values in multiple testing (Holm, 1979) have been utilized. As level of significance for all test decisions alpha = 0.05 has been used. All visualizations and statistical analyses are based on difference values calculated from the hourly mean logger data and the corresponding hourly data from the Augsburg-Mühlhausen reference station.

Table 2

Synoptic categories, defined as specific combinations of magnitudes of wind speed (ws) and cloud cover (cc) amounts at Augsburg-Mühlhausen. Numbers in cells indicate the sample sizes of categories (respective number of available hourly observations).

Windspeed– ws [m/s] cloud cover– cc [1/8]	$ws \leq 2$	$2 < ws \leq 4$	$4 < ws \leq 6$	$ws > 6$
$cc \leq 2$	1886	1076	298	106
$2 < cc \leq 4$	297	236	84	43
$4 < cc \leq 6$	377	292	116	79
$6 < cc \leq 8$	4328	4284	1881	1140

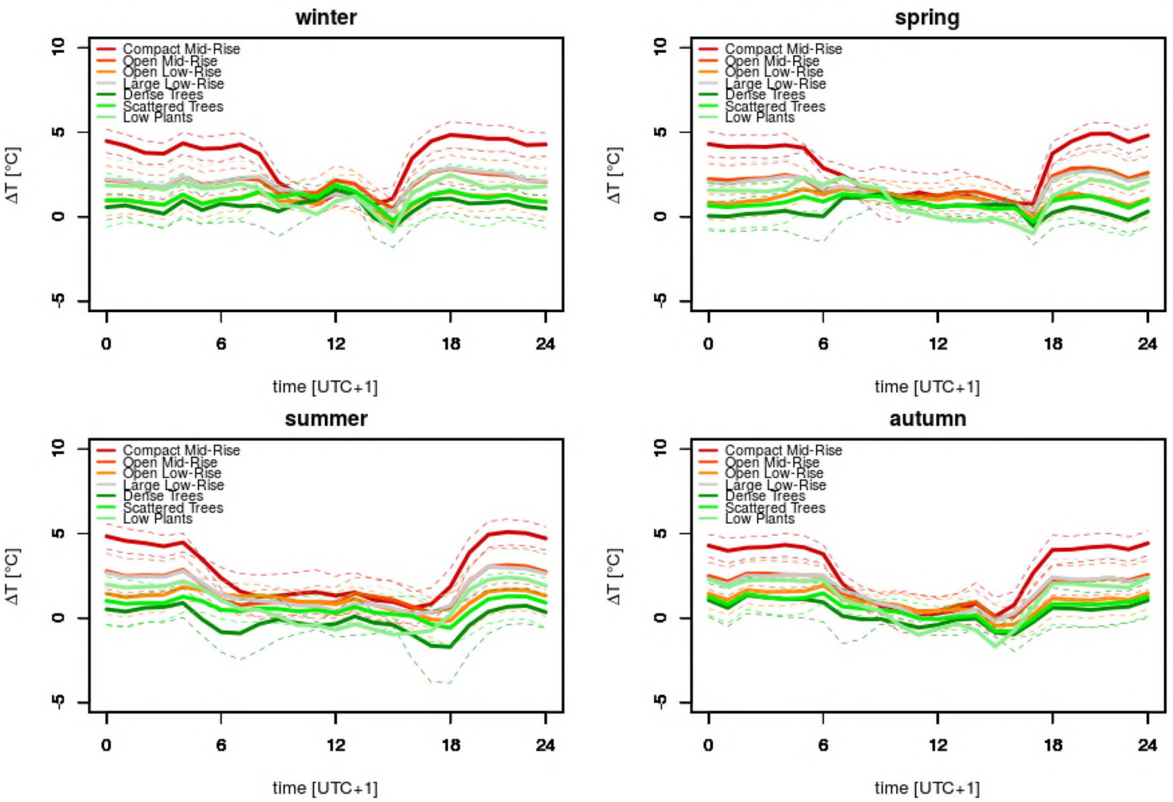

Fig. 8. Mean diurnal cycles of air temperature differences (ΔT) between local climate zones and the reference station Augsburg-Mühlhausen under "favourable" synoptic conditions (wind speed < 2 m/s, cloudcover < 2 octas), for the four three month seasons winter (DJF), spring (MAM), summer (JJA) and autumn (SON). Bold solid lines show the mean values over all sites of the respective LCZ type; dashed lines indicate the respective ± onefold standard deviation.

3. Results

In this section we first briefly illustrate the differences in thermal characteristics of LCZ categories in the urban area of Augsburg as realized under synoptic boundary conditions that are highly favourable for the development of urban-rural and intra-urban climatic differences. Secondly, we explicate the dependance of differences in air temperatures among LCZ categories on the corresponding synoptic state.

3.1. Thermal differences among LCZ types under favourable synoptic situations

As „favourable "synoptic boundary conditions we here define weather situations – as observed at the Augsburg-Mühlhausen reference station - featuring wind speeds below 2 m/s and a cloud cover of < 2 octas. Diurnal variations of the thermal differences arising between LCZ types and the Augsburg-Mühlhausen reference station under such synoptic conditions are depicted in Fig. 8 for the four three month seasons (DJF, MAM, JJA, SON).

As can be seen from Fig. 8, air temperature differences between different LCZ types and the Augsburg-Mühhausen reference station reach partly remarkable intensity in particular during the nocturnal radiation period in all four seasons. Highest positive difference values appear for the built up LCZ categories reaching up to 5 °C for Compact Mid Rise in summer during the nighttime. LCZ types Large Low Rise and Open Mid Rise feature positive differences of up to approximately 3 °C and the least artificial built up category Open Low Rise exhibits differences mostly below 2 °C. During the day air temperatures of all four built up categories are approaching temperatures at Augsburg-Mühlhausen. However, with differences remaining positive reaching up to around 2 °C. Among the natural LCZ types the Low Plants category features highest positive air temperature differences partly reaching higher values than the built up Open Low Rise class. In most cases smallest positive or even slightly negative air temperature differences appear for the two forested LCZs Dense Trees and Scattered Trees.

Concerning the statistical significance of the detected LCZ related variations in air temperature differences Kruskal-Wallis tests and pairwise Wilcoxon rank sum tests have been performed as outlined in Section 2.6. Results from the application of these tests are displayed in Fig. 11. With regard to the here considered favourable synoptic conditions, we refer only to the respective bottom left panel of each seasonal plot given in Fig. 11.

For all four seasons the null hypothesis of the Kruskal-Wallis test and as well the null hypothesis of the pairwise Wilcoxon rank

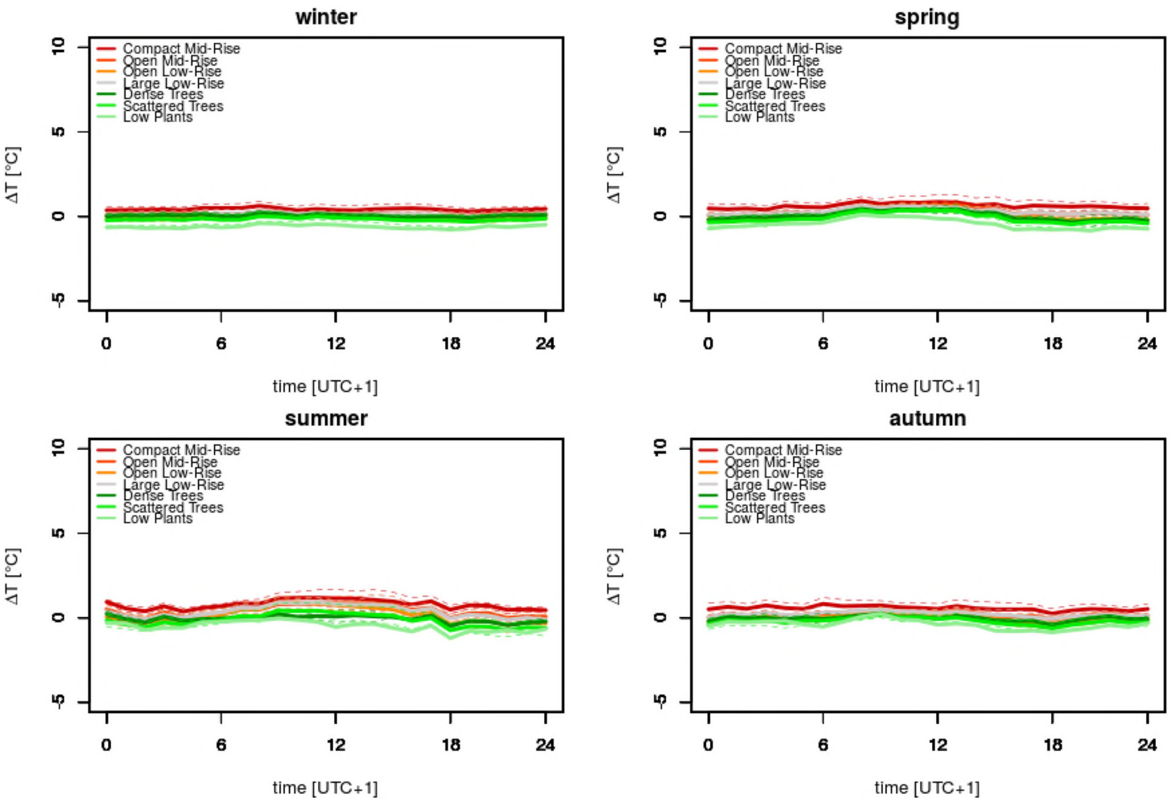

Fig. 9. As Fig. 8 but for "unfavourable" synoptic conditions (wind speed ≥ 4 m/s, cloudcover ≥ 4 octas).

sum test can be rejected on a 95% (alpha = 0.05) level of significance for the overwhelming fraction of the day. At the most for the hours between 9 and 15 UTC + 1 no significance is reached for the Kruskal-Wallis test and/or the pairwise Wilcoxon rank sum test in winter, spring and autumn. As can already be deduced from Fig. 8, in most cases Compact Mid Rise features highest positive temperature differences whereas Dense Trees most often exhibits smallest positive – or even negative – differences to the reference station Augsburg-Mühlhausen. However, among the warmest LCZs also Open Mid Rise, Open Low Rise and Large Low Rise appear in some cases and Scattered Trees and Low Plants occasionally feature the coldest conditions.

3.2. Influence of varying synoptic boundary conditions on thermal LCZ characteristics

Results presented in the preceding section confirm findings on LCZ related differences in thermal characteristics under ideal undisturbed synoptic conditions allowing for intense nocturnal cooling that have been reported for other urban regions (e.g. Stewart et al., 2014; Lehnert et al., 2015; Gál et al., 2016). In how far LCZ related thermal differences persist or change under synoptic boundary conditions with increasing wind speed and/or increasing cloud cover is depicted in the following.

Fig. 9 illustrates diurnal cycles of air temperature differences between different LCZ types and the Augsburg-Mühhausen reference station for highly unfavourable weather situations (windspeed ≥ 4 m/s, cloudcover ≥ 4 octas). Air temperature differences under such boundary conditions mostly remain in the range ± 1 °C. However, a rather clear cut distinction between LCZ categories can be seen. Highest positive differences appear in all four seasons and for all hours of the day for Compact Mid Rise. The remaining three built up LCZ categories feature only slight positive differences. Difference values related to Dense Trees are mostly close to zero while the other two natural LCZs mostly exhibit slightly negative differences with Low Plants being the coldest LCZ type. Albeit the rather small differences among LCZ categories under disturbed weather conditions Kruskal-Wallis and pairwise Wilcoxon rank sum tests frequently proof statistical significance of the influence of the LCZ categorization onto air temperature differences. This can be seen from the respective panels in Fig. 11. Statistical significance for both tests appears in particular for situations with > 6/8 cloud cover and wind speeds of > 4 m/s. For less cloudy conditions (4–6 octas) combined with the above specified wind speed characteristics no tests could be performed or no significance could be reached for numerous hourly subsets. Both findings may be related to the rare occurrence of these weather situations (see Table 2) resulting in missing or rather small samples for the high temporal resolution of one hour.

In addition to the rather specific examples provided for differences in the LCZ specific thermal characteristics for highly favourable (Fig. 8) and unfavourable (Fig. 9) weather situations a more general view on the dependency of air temperature differences between LCZ categories and the Augsburg-Mühlhausen reference station on the synoptic boundary conditions is given in Fig. 10.

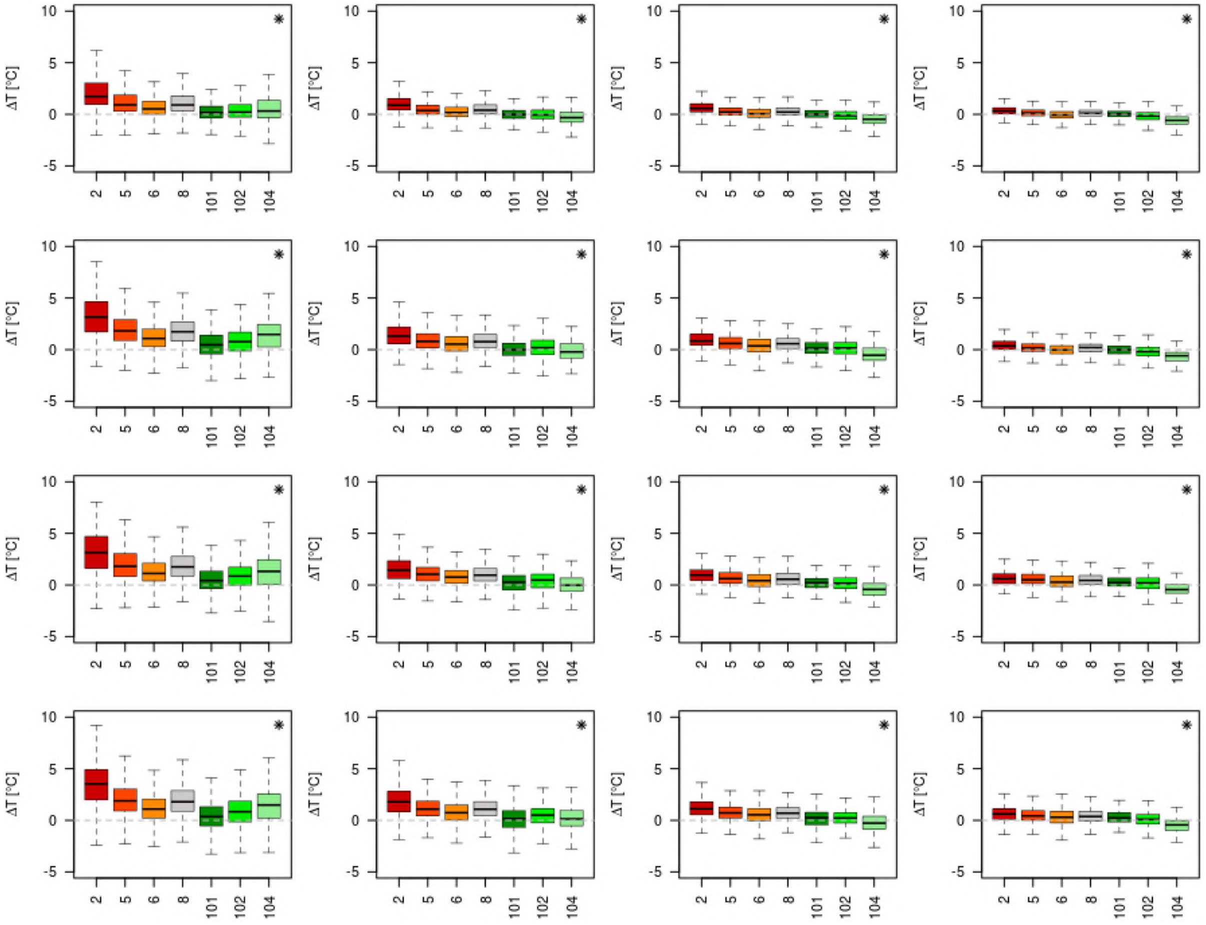

Fig. 10. Boxplots of air temperature differences (ΔT) between local climate zones and the reference station Augsburg-Mühlhausen. Boxplots include the median, the 1st and 3rd quartile; whiskers indicate the highest/lowest value inside the interval defined by ± the 1.5-fold interquartile range from the 1st/3rd quartile. LCZ-categories on the x-axis are: 2– Compact Mid Rise, 5– Open Mid Rise, 6– Open Low Rise, 8– Large Low Rise, 101– Dense Trees, 102– Scattered Trees, 104– Low Plants. Boxplots incorporate data from all seasons and all times of the day. A star in the top right corner of each plot indicates statistical significance (alpha = 0.05) of a Kruskal-Wallis test applied to the data displayed in the respective plot. Synoptic boundary conditions vary among the 16 sets of boxplots as follows: windspeed (ws in m/s) varies from the left column to the right column (ws ≤ 2; 2 < ws ≤ 4; 4 < ws ≤ 6; ws > 6), cloud cover (cc in octas) varies from the bottom row to the top row (cc ≤ 2; 2 < cc ≤ 4; 4 < cc ≤ 6; 6 < cc ≤ 8).

First to mention is that concerning all subsamples statistical significance of the influence of LCZ categorization onto thermal characteristics (expressed as air temperature differences to the reference station Augsburg-Mühlhausen) can be deduced from the applied Kruskal-Wallis tests. Not surprisingly, it is quite obvious from the boxplots displayed in Fig. 10 that the thermal differences among LCZ types diminish with increasing degree of synoptic disturbances (increasing wind speed and increasing cloud cover). In this context, the influence of increasing wind speed appears to be far more important than the effect of increasing cloud cover. Whereas thermal differences among LCZ categories substantially persist along the columns (categories of cloud cover) of panels in Fig. 10 distinct declines in thermal dissimilarity among LCZs appear along the rows (categories of wind speed) of panels in Fig. 10.

A quite remarkable difference between the category of lowest wind speed (ws ≤ 2 m/s) and the adjacent higher wind speed categories - in particular those categories featuring wind speeds above 4 m/s – can be stated with respect to the order of the LCZ specific air temperature differences. Whereas among the four built up LCZ types the ordering of difference values remains stable over all wind speed categories (from warmest to coolest - Compact Mid Rise, Open Mid Rise, Large Low Rise, Open Low Rise) the ordering of the natural LCZs according to their air temperature characteristics is inverted between the lowest wind speed category (from coolest to warmest - Dense Trees, Scattered Trees, Low Plants) and the more windy (and cloudy) weather situations (from coolest to warmest - Low Plants, Scattered Trees, Dense Trees).

The overall generalized picture of weather related deviations in thermal LCZ characteristics depicted inFig. 10 is further detailed in Fig. 11. From Fig. 11 for each season (DJF, MAM, JJA, SON), every hour of the day (0–23 UTC + 1) and 16 different synoptic categories (4 wind speed categories by 4 cloud cover categories) the respective warmest and coldest LCZ type (with respect to their specific air temperature differences to the Augsburg-Mühlhausen reference station), the statistical significance of the LCZ

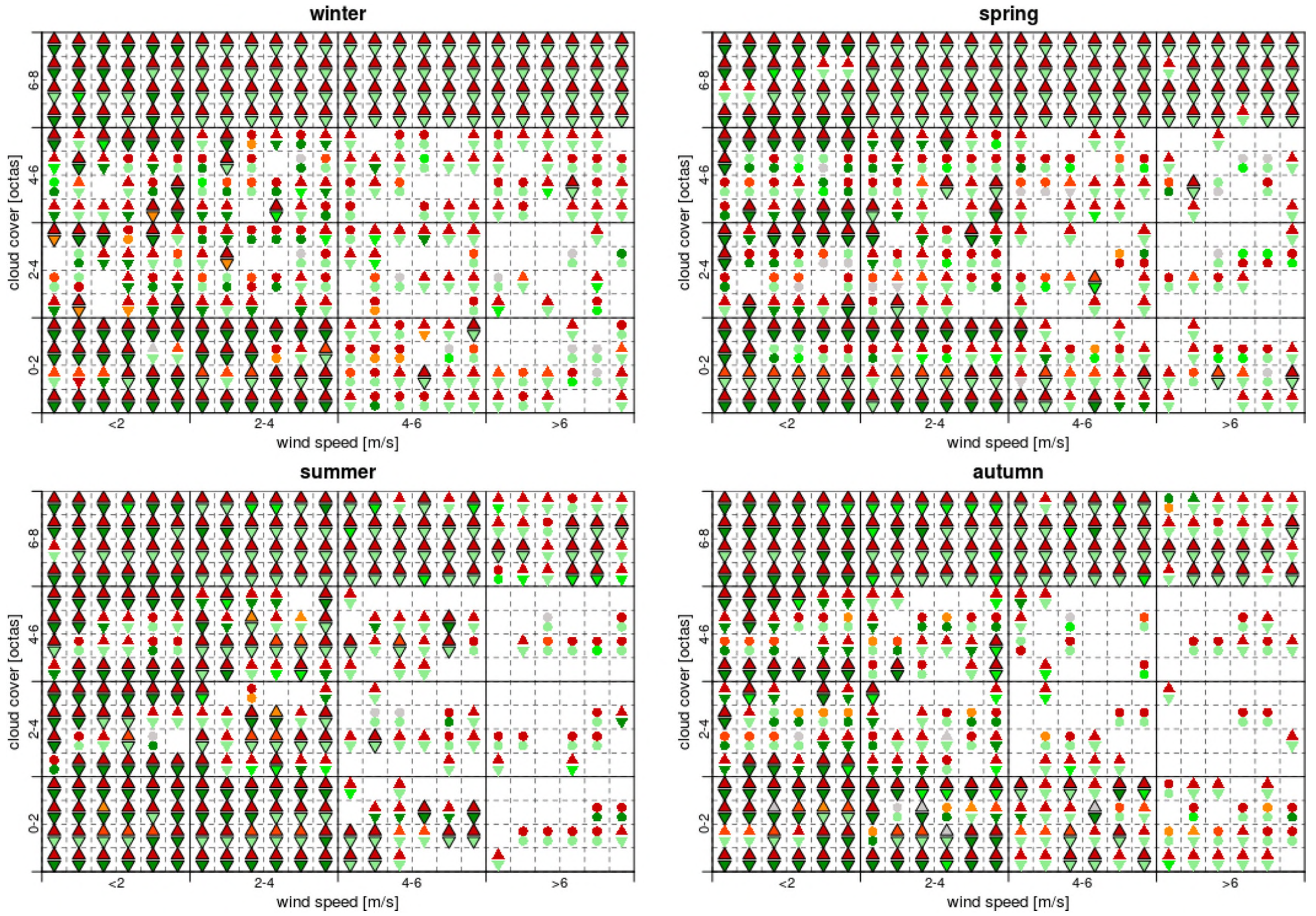

Fig. 11. Results of Kruskal-Wallis tests and pairwise Wilcoxon rank sum tests applied to air temperature differences between LCZ categories and Augsburg-Mühlhausen reference station. Statistical tests have been performed for the four seasons winter (DJF), spring (MAM), summer (DJF) and autumn (SON; for each hour of the day (0 – 23) and for the varying synoptic boundary conditions as displayed in Table 2. Test results for hours of the day are organized in each "synoptic" panel from the top left cell (0 UTC + 1) to the bottom right cell (23 UTC + 1); empty cells indicate insufficient sample size for the respective selection. Coloured upper/lower symbols (triangles, circles) in each cell indicate the LCZ categories featuring the highest/lowest air temperature difference to the Augsburg-Mühlhausen reference station. Colour codes for LCZs are identical to those used in preceding Figures. Triangles denote statistical significance (alpha = 0.05) of the Kruskal-Wallis test, framed triangles denote additionally statistical significance (alpha = 0.05) of the pairwise Wilcoxon rank sum test concerning the two displayed LCZ categories. Circles indicate that neither for the Kruskal-Wallis test nor the pairwise Wilcoxon rank sum test statistical significance could be deduced.

categorization with respect to air temperature characteristics and the statistical significance of differences in air temperature between warmest and coldest LCZ types respectively can be deduced.

Main evidence from Fig. 11 confirms that the most intensely built up LCZ category Compact Mid Rise in the majority of cases features highest positive air temperature anomalies with respect to the Augsburg-Mühlhausen reference station under all weather situations, in all seasons and during all times of the day. The very few exceptions from this finding appear mainly during the day. The change in the order of air temperature anomalies of natural LCZ types along weather categories that has been stated above for seasonally and daily merged data (Fig. 10) can be confirmed for the seasonally and daily disaggregated data in Fig. 11 as well. Low Plants emerges as the coldest LCZ type under more disturbed – higher wind speed/amount of cloud cover - weather situations. In particular in the daytime, the Low Plants category partly also appears to be the coldest LCZ under synoptic conditions that are favourable for the development of intra-urban temperature differences. A striking feature in Fig. 11 is the numerous missing or insignificant results for those weather situations with wind speeds above 4 m/s and cloud cover below 6 octas and – less distinct – for weather situations characterized through wind speeds below 4 m/s and cloud coverage between 2 and 6 octas. This is apparently related to the rather rare occurrence of these weather situations in the Augsburg area (see Table 2) leading to either unfeasible statistical tests or to preferred non-significant test results due to small sample sizes.

4. Discussion and conclusions

Most previous investigations of the climatological characteristics of LCZ categories and the respective differences have considered the overall weather conditions (without any selection of specific situations) and ideal calm and clear weather conditions (low wind speed and small cloud cover), the latter being highly favourable for the development of urban-rural and intra-urban climatic differences related to specific surface structures (e.g. Lehnert et al., 2015; Gál et al., 2016; Skarbit et al., 2017). In contrast, the main aim of the here presented study was to contribute to the climatological evaluation of the LCZ scheme explicitly taking into consideration varying weather situations (synoptic boundary conditions). In particular, we were able to quantify how increasing values of wind speed and cloud cover diminish the thermal differences between LCZ categories.

Our analyses were based on an LCZ mapping of the urban area of Augsburg (Bavaria, Southern Germany) and hourly aggregated air temperature data from a comprehensive logger network. Utilizing thoroughly quality checked air temperature data from logger locations which could be unambiguously assigned to particular LCZ categories and temperature data from a reference station we investigated the air temperature differences between four built up and three natural LCZ types and the reference station. We stratified the data into 16 different weather situations according to categories of wind speed and cloud coverage measured at the Augsburg-Mühlhausen reference station. The definition of weather situations or synoptic situations we used is rather arbitrary. Alternatively it would have been possible to discriminate weather situations utilizing the weather factor developed by Oke (1998). However, the simple stratification used in this study has the advantage that the influencing effects of wind speed and clouds could be easily separated in a straightforward way.

Our findings on air temperature characteristics of LCZ categories for weather situations that are highly favourable for differential heating and cooling of different surface structures are in agreement with results reported in the literature (e.g. Gál et al., 2016; Lelovics et al., 2014; Skarbit et al., 2017). Firstly, we found clear-cut differences in thermal characteristics between built up LCZ categories and natural LCZ types, with the built up LCZs featuring higher temperatures than the natural ones. Secondly, among the built up LCZcategories a distinct order with respect to the air temperature deviations from the reference station became obvious with temperatures decreasing from Compact Mid Rise over Open Mid Rise and Large Low Rise to Open Low Rise.

Under increasingly disturbed weather conditions the air temperature differences among LCZ categories – not surprisingly – decrease. Thereby, the attenuation of the thermal differences occurs much faster with increasing wind speed than with increasing cloud coverage. Even for overcast conditions in combination with low wind speeds remarkable air temperature differences among LCZs can be observed. Statistical tests (Kruskal-Wallis test, pairwise Wilcoxon rank sum test) provided proof for the statistical significance of the influence of LCZ categories on thermal characteristics, even under strongly disturbed synoptic conditions. For a number of specific weather situations no statistical tests could be performed or no statistical significance could be detected, mainly because of rather small sample sizes. However, these small sample sizes reflect the rarity of the respective weather situations in the study area and are not due to any inconsistencies of the underlying observational data base.

Our finding that specific thermal characteristics of LCZ categories in our study area are not only evident under „ideal “undisturbed synoptic conditions but persist – although increasingly diminished – also under disturbed conditions characterized by higher wind speeds and higher cloud coverage is important as ideal weather situations are not the most commonly occurring synoptic conditions in our study area (as can be seen from Table 2). The knowledge of weather situations – in particular those with noteworthy occurrence frequencies - under which relevant thermal differences among LCZ types can be expected is relevant for instance for urban planners. Moreover, the quantification of the thermal characteristics of LCZ types for different weather situations gains importance in due consideration of climate change aspects. As frequencies of certain large scale weather types are expected to change under potential future climate change conditions (e.g. Jacobeit et al., 2017) it can be also expected that the frequencies of specific weather situations in the study area will change. Hence, thermal LCZ differences under specific synoptic conditions are one important parameter for estimating potential effects of climate change on the urban environment.

However, in addition to determining the statistical significance of thermal LCZ differences as it has been done in this study it will be an important task to be tackled in future research to investigate in how far thermal LCZ differences under disturbed weather situations are relevant from a human bioclimatological point of view. To this end, health relevant metrics like for instance the physiologically equivalent temperature (PET) have to be derived and analysed with respect to their LCZ specific characteristics (Unger et al., 2017) under varying weather situations.

Recent studies suggest that sudden weather changes may have distinct adverse effects on human health (e.g. Rakers et al., 2016). Such rapid weather changes on the local scale – for example sharp rises in temperature - are related to specific synoptic situations like for instance the passage of frontal systems. Within the urban environment the magnitude and the effects of these rapid changes may be damped or fostered depending on the urban surface structure as for instance represented by the LCZs. On the basis of our temporally high resolved (4-min intervals, enabling the derivation of variable temporal data aggregations on the sub-hourly to sub-daily time scale) urban climatological data base the characteristics and effects of rapid weather changes and as well their respective LCZ specific variations will be analysed in future investigations.

Finally, taking into account the potential effects of LCZ categories on human health a further important extension will be the consideration of the spatial patterns of air quality parameters in our study area (Wolf et al., 2017). This way it is aspired to take into account combined potential health related effects of climatic features and air quality (Breitner et al., 2014). As for the thermal characteristics of the LCZ categories such integrated health related characteristics are expected to feature variations due to the synoptic boundary conditions.

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