Using Land Cover, Population, and Night Light Data for Assessing Local Temperature Differences in Mainz, Germany

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(Manuscript received 8 May 2014, in final form 8 December 2014)

ABSTRACT

Urban areas are believed to affect temperature readings, thereby biasing the estimation of twentieth-century warming at regional to global scales. The precise effect of changes in the surroundings of meteorological stations, particularly gradual changes due to urban growth, is difficult to determine. In this paper, data from 10 temperature stations within 15 km of the city of Mainz (Germany) over a period of 842 days are examined to assess the connection between temperature and the properties of the station surroundings, considering (i) built/paved area surface coverage, (ii) population, and (iii) night light intensity. These properties were examined in circles with increasing radii from the stations to identify the most influential source areas. Daily maximum temperatures T_{max}, as well as daily average temperatures, are shown to be significantly influenced by elevation and were adjusted before the analysis of anthropogenic surroundings, whereas daily minimum temperatures T_{min} were not. Significant correlations ($p < 0.1$) between temperature and all examined properties of station surroundings up to 1000 m are found, but the effects are diminished at larger distance. Other factors, such as slope and topographic position (e.g., hollows), were important, especially to T_{min}. Therefore, properties of station surroundings up to 1000 m from the stations are most suitable for the assessment of potential urban influence on T_{max} and T_{min} in the temperate zone of central Europe.

1. Introduction

It is well known that anthropogenic changes in land cover and land use (LCLU) can impact climate, with the most pronounced effects found in urban areas. A changed energy balance caused by many factors—increased thermal admittance of urban materials, limited radiative and advective cooling due to the urban geometry, lowered evapotranspiration cooling due to sealed surfaces and limited vegetation coverage, and anthropogenic heat release—tend to increase air temperatures in urban areas compared to the rural zones (e.g., Arnfield 2003). This so-called urban heat island (UHI) effect is generally most pronounced in larger settlements with dense urban structure and sparse vegetation (e.g., Oke 1982), and has been found in urban areas all over the world (Wienert and Kuttler 2005). However, the UHI effect has also been observed in smaller towns (Magee et al. 1999; Torok et al. 2001; Kolokotsa et al. 2009; Steeneveld et al. 2011), and even in small villages—for example, Barrow, Alaska (population 4600), where the built area was on average 2.2°C warmer than its surroundings during winter (Hinkel et al. 2003). Anthropogenic changes in rural vegetation cover can also cause considerable temperature differences (Hawkins et al. 2004; Lindén 2011), and significant reductions in daily maximum temperature and daily temperature range (DTR) have been connected to irrigation practices (Mahmood et al. 2004; Lobell and Bonfils 2008).

Information on anthropogenic influence on climate can be used for improving the comfort, energy use, and health of inhabitants in urban areas, but is also of interest when estimating regional and large-scale surface warming trends. Metadata from long-term meteorological stations often reveal that instruments were situated in small

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DOI: 10.1175/JAMC-D-14-0124.1

towns that over the years have developed into larger towns or cities. The temperature records of these stations may have been affected by the growth of the UHI and could, therefore, show temperature trends not caused only by changes in regional climate (Jones and Wigley 2010; Venema et al. 2012). Although several studies indicated UHI effects on large-scale temperature data to be small (e.g., Parker 2006; Trenberth et al. 2007; Parker 2010), other work has indicated considerable UHI influences in rapidly urbanizing China (Jones et al. 2008; Ren et al. 2008; He et al. 2013) and the United States (Hansen et al. 2001), for example.

Approaches for removing anthropogenic influence in studies of long-term temperature trends include the exclusion of sites showing urban warming; adjustment of urban records to match nearby rural observations; analysis of temperatures in windy, cloudy weather (when the urban effect is considerably weakened); analysis of, or comparison with, trends in ocean surface temperatures; and the use of atmospheric reanalyses (Parker 2010). Studies aiming to exclude stations showing urban warming generally divide stations into a basic classification of urban, sub–peri-urban, and rural classes (Peterson and Vose 1997; Hansen et al. 2010; Das et al. 2011). Since anthropogenic warming influences are connected to changes in the LCLU, this type of data would be most suited for station classification, but proxies are often used instead, for example, satellite-based imagery of nighttime surface lights (Elvidge et al. 1997; Peterson et al. 1999; Peterson 2003), or population data (Peterson and Vose 1997; Owen and Gallo 2000; Hua et al. 2008). However, the suitability of these differing schemes for station classification has not been thoroughly tested, and studies show that variable results can be found (Peterson et al. 1999; Hansen et al. 2001; Peterson and Owen 2005). Jones et al. (2008) showed that consideration of population metadata leads to biased results, and Parker (2010), as well as Hansen et al. (2010), suggest that night light data produce more robust estimates of UHI effects on temperature readings.

The thermal source area influencing temperatures at standard screen height depends on, for example, weather conditions, surface geometry, and the duration of the study period, and can extend upwind for meters to kilometers (Stewart and Oke 2012), but the most representative source area for LCLU is often 500 m or less in urban areas (Li and Roth 2007; Hart and Sailor 2009; Yokobori and Ohta 2009; Lindén 2011). Steeneveld et al. (2011) also shows that the UHI were more closely related with population density at neighborhood scale than to the number of total inhabitants in the city. A spatially detailed study by Gallo et al. (1996) revealed that, in rural areas also, the LCLU in the nearest 100 m of U.S. Historical Climatological Network stations had a stronger influence on DTR when compared with 1000- and 10 000-m distances. However, studies of continental or global temperature trends often use a larger source area, for example, grid sizes of 3 km × 3 km (Gallo and Owen 1999; Peterson et al. 1999; Hansen et al. 2001; Hansen et al. 2010) and coarse population data (Peterson and Vose 1997; Gallo and Owen 1999; Hansen et al. 2001; Ren et al. 2008; Das et al. 2011). Peterson and Owen (2005) concluded that no UHI contamination was found in the United States if stations exceeding 30 000 inhabitants within 6 km were excluded from the dataset. However, in densely inhabited areas, this scheme may exclude the majority of the stations and, especially, stations with very long temperature records, as these are frequently located near urban areas (Jones and Wigley 2010). Studies showing the most influential source area for stations located outside of major urban areas, but in areas with considerable anthropogenic influence (agricultural and semiurban areas, etc.), are few.

In this paper, screen height temperatures from 10 stations in agricultural or semiurban settings within 15 km from the city of Mainz, Germany, are examined with a focus on determining the association between station temperatures and land cover (built/paved surface cover), population density, and night light intensity within 100, 300, 1000, and 3000 m. Results are discussed in view of the influence of station surroundings on temperature and thus suitability as a station classification parameter. Additional factors influencing temperatures, such as relief and vegetation type, are also discussed.

2. Data and methods

The German city of Mainz has 200 000 inhabitants (2100 inhabitants per square kilometer) and is situated in eastern Rhineland-Pfalz at 50.0°N and 8.3°E in a landscape of rolling hills with the Rhine River (as the border with Hessen) and the cities of Wiesbaden (population 270 000) and Frankfurt (population 700 000) to the north and east and mainly agricultural areas with smaller villages to the south and west (Fig. 1). The area is relatively densely inhabited, with an overall population density of 200 inhabitants per square kilometer in Rhineland-Pfalz, and 290 inhabitants per square kilometer in the neighboring state of Hessen. The climate is temperate maritime (Köppen classification Cfb), with monthly average air temperatures ranging from 1.9° to 20.8°C, and precipitation ranging from 40 to 76 mm month $^{-1}$ (average for 1981–2010; http://www.dwd.de).

The 10 rural or semiurban stations are part of a statewide network of agrometeorological stations operated by the state of Rheinland-Pfalz (http://wetter.rlp.de). Eight

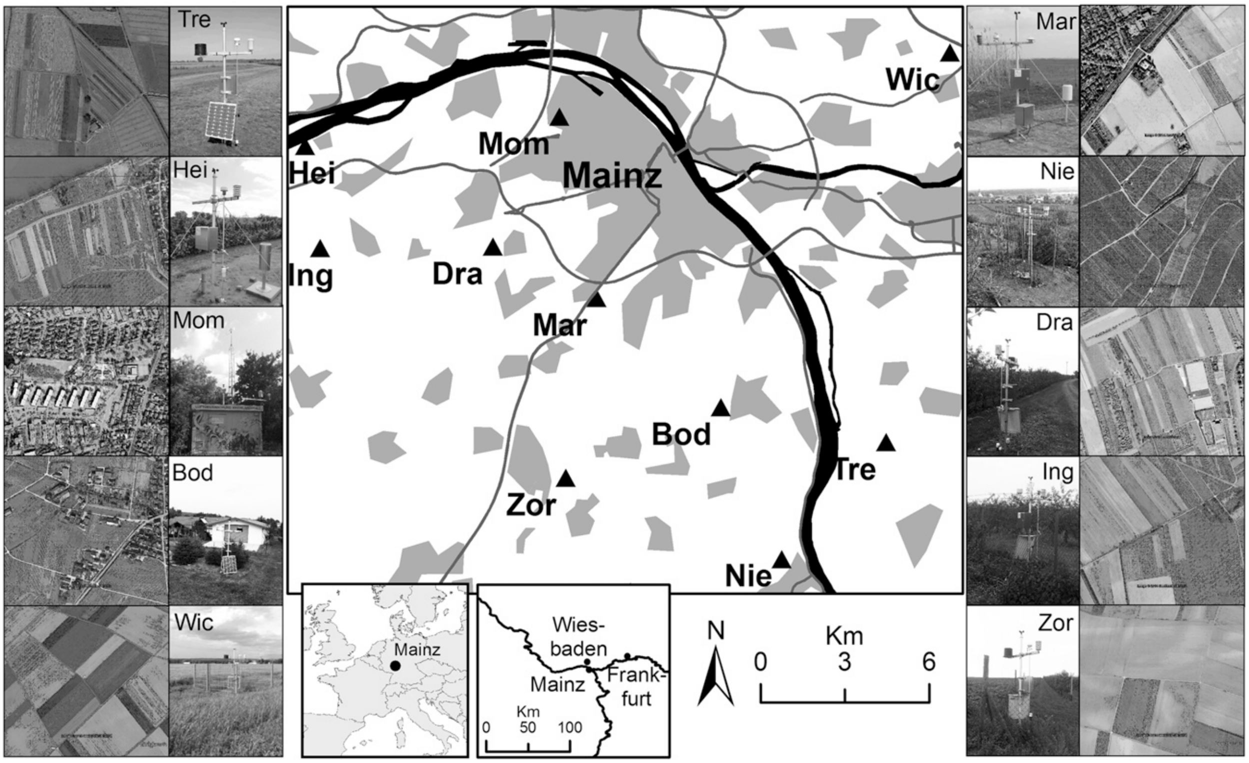

FIG. 1. Locations and photographs of temperature stations. Built areas are shown in light gray, rivers are black, and main roads are dark gray. Satellite images are 600 m × 600 m (copyright Google Earth) centered on the stations. Station abbreviations are Mom, Mombach; Mar, Marienborn; Ing, Ingelheim; Wic, Wicker; Dra, Drais; Tre, Trebur; Zor, Zornheim; Hei, Heidenfahrt; Bod, Bodenheim; and Nie, Nierstein.

of the stations are located in Rhineland-Pfalz while the other two are on the opposite side of the Rhine River in Hessen (Fig. 1 and Table 1). All stations were visited to classify the surroundings (within 100 m) in view of dominating local climate zones (LCZ; Stewart and Oke 2012), land cover, slope, and aspect. Nine stations are clearly defined as being of a rural character (mainly low plants or scattered trees), although two stations also had sparsely built surroundings. These stations are mounted on free-standing masts and generally fulfill the World Meteorological Organization guidelines for the siting of temperature sensors (some stations may be slightly closer to trees than

TABLE 1. Description of station surroundings, slope/aspect, vegetation height, and altitude. LCZ as detailed in Stewart and Oke (2012) describes the built structures (5 = open midrise; 9 = sparsely built) and land cover (B = scattered trees; D = low plants).

Station name (as referred to in text)	LCZ	Detail	Slope/aspect (within 100 m)	Vegetation height (m)	Alt (MSL)
Trebur (Tre)	D	Short crops	1°/SE	<1*	85
Heidenfahrt (Hei)	B	Fruit orchards near river, shallow low area around station	1°/N	~2.5	88
Mombach (Mom)	5	Suburban residential area, low grass, trees and bushes	3°/N	2–4	120
Bodenehim (Bod)	9	Vineyards, vertically oriented rows	5°/NE	~1.5	120
Wicker (Wic)	D	Short crops	3°/SE	<1*	140
Marienborn (Mar)	9	Farm near village, low crops	3°/NE	<1*	153
Nierstein (Nie)	B	Wine fields, vertically oriented rows	18°/SE	~1.5	169
Drais (Dra)	B	Fruit orchards, shallow low area around station, horizontally oriented rows	2°/E	~2.5	207
Ingelheim (Ing)	B	Fruit orchards	1°/N	~2.5	219
Zornheim (Zor)	D/B	Short crops/newly planted fruit orchards, hilltop location	2°/W	<1* <2.5	238

* Vegetation height varies throughout the year from 0 to approximately 1 m.

guidelines suggest). The 10th station, Mom (see Table 1 for a complete listing of the station names and identifiers), is located on the outskirts of the urban area but still falls within the borders of the city of Mainz, and has urban elements in its near surroundings (open midrise buildings). This station was mounted on the east side of a small building at a distance of 1.5 m from the wall. The east wall of this building is shaded from direct sunlight by shrubs and trees located a few meters away, and the temperature sensor is therefore not exposed to radiative heat from the wall. The influence of the trees and the small buildings was considered in our analysis. The stations were located in varying relief with slopes ranging from 1° to 18°. Two stations were located in shallow low points (estimated depth less than 2 m) of the terrain. Two main vegetation types were present (crop or wine fields categorized as low plants, or fruit orchards categorized as scattered trees). While none of the sites was intensely irrigated, drip irrigation systems have been installed near those stations surrounded by fruit orchards. The fruit orchards may have been irrigated during the study period, though detailed information the amount and timing was not available.

We here use hourly temperature data from 10 stations from 2011, 2012, and 2013 until 16 July. A period of 87 days in 2011 (18 April–13 July) was excluded because of missing data at one of the stations, resulting in a total of 842 days being included in the analysis. All temperature data were measured using Hoffman Messtechnik Pt-1000 sensor elements placed at 2 m above ground in a radiation shield and ventilated by miniature fans (about 2 m s^{-1}). The sensors cover from −25° to + 70°C and with a total error $< \pm 0.2$°C between −25° and +50°C (including errors in cables, connectors, and electronics). The instruments were calibrated by the manufacturer prior to installation and comply with the micrometeorological standards used in Germany (DIN/VDI 3786; Foken 2008). For station classification, the percentage of built or paved (impermeable) surfaces, level of night lights, and populations within distances of 100, 300, 1000, and 3000 m of the stations were determined. Land cover and population density at these distances were determined using georeferenced shape files of natural surfaces, buildings, roads, and land use (available online at http://www.geofabrik.de) and analyzed using the ArcGIS system. Satellite images from Google Earth were consulted to validate the accuracy of the land cover and building data. This procedure revealed a number of missing buildings in the downloaded shape files, which were subsequently manually digitalized to create a complete file for the determination of the built/paved area surface coverage and built/paved surface in the station surroundings. Population data were validated against 2012 statistics found online (http://www.statistik.rlp.de and http://www.statistik-hessen.de) and mapped ascribing the number of inhabitants to a point in the center of a polygon indicating the spatial extent of a city/village. Where populated areas were only partly within predefined station distances, and neighborhood statistics were also unavailable, the population was assumed to be equally distributed throughout a village. Because of the uncertainty in the population data, numbers were rounded to the nearest 50 m within 1000 m and the nearest 500 m within 3000 m from a station. For the 100- and 300-m radii, the population was estimated based on the number and type of residential houses, considering three inhabitants for single-family houses and two inhabitants for apartments (average number of people per household in Germany is 2.2; see http://www.destatis.de). For the determination of night lights, satellite images provided by the Earth Observation Group, NOAA/National Geophysical Data Center (NGDC), with the Visible Infrared Imaging Radiometer Suite (VIIRS) were downloaded from the NGDC website (http://ngdc.noaa.gov/eog/viirs.html). A monthly composite from October 2012, generated using VIIRS day/night-band data collected on nights with zero moonlight and cloud cover (a minimum of nine cloud-free observations are merged for each pixel), was selected for analysis (Fig. 2). These images have a resolution of approximately 375 m and show the radiance [nW $(cm^2\,sr)^{-1}$]. The images were imported into the ArcGIS system and the average night light intensities within 100, 300, 1000, and 3000 m from each station were calculated. The data for the 100-m radius should be regarded with caution since the image resolution exceeds this distance. The area of the Rhine River was given a 0 (no light) in the night light analysis.

Hourly temperature data were used to determine daily maximum ($T_{\max}$), average (T_{avg}), and minimum ($T_{\min}$) temperatures, as well as DTR. The daily departure ΔT for each station $T_{\text{avg/min/max}}$ and DTR from the daily mean of all stations was calculated [e.g., at Trebur daily $\Delta T_{\text{avg(Tre)}}$ = daily $T_{\text{avg(Tre)}}$ – daily $T_{\text{avg(all)}}$]. Median values for the total 842-day period, as well as for different seasons, for each station and temperature parameter (avg, min, max, and DTR), were used to calculate the coefficients of determination of temperature and built/paved area surface coverage, population, and night light intensity in the station surroundings. To examine whether the two vegetation types present at the sites (low plants and scattered trees) influenced the total and seasonal $T_{\text{max/avg/min}}$ and DTR, an independent-samples *t* test was applied.

3. Results

a. Station network temperatures

Based on median values for each station for the 842-day period, the network ranges of $T_{\text{max/avg/min/DTR}}$

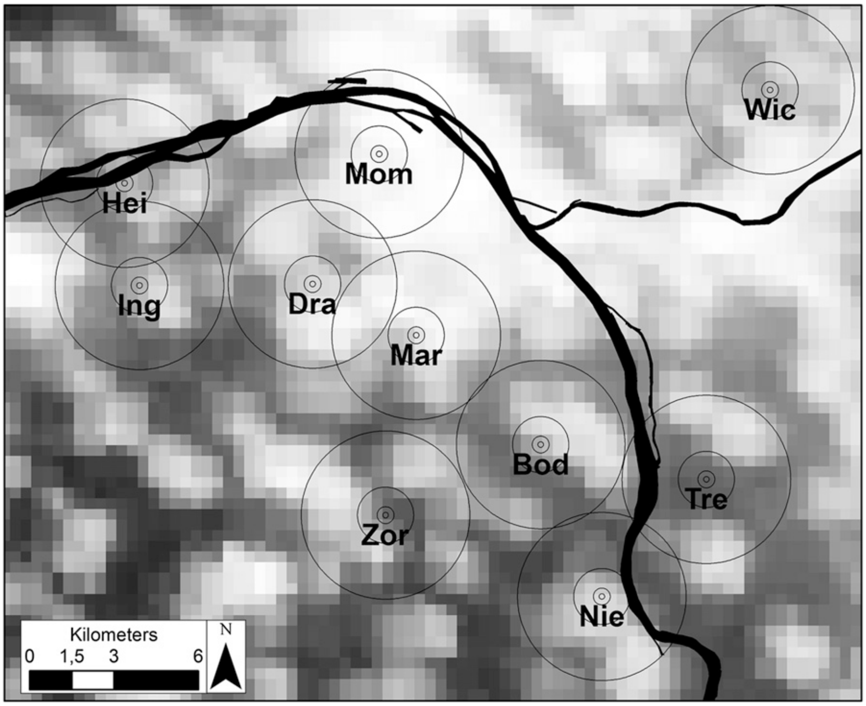

FIG. 2. Map of night light intensity [nW $(cm^2\ sr)^{-1}$] for the Mainz area. The circles indicate the radii considered for the surroundings at 100, 300, 1000, and 3000 m. Night light intensity in the image ranges from 0 to 62 nW $(cm^2\ sr)^{-1}$. (The image was produced and made available by the Earth Observation Group, NOAA/NGDC.)

were 2.2°, 1.4°, 1.8°, and 2.1°C, respectively. Seasonal network ΔT_{max} and ΔT_{avg} were smallest in the wintertime (1.6° and 1.4°C) and were larger during the summer (3.0° and 1.7°C; Figs. 3a,b). Additionally, ΔT_{min} was also smallest in winter (1.5°C) but highest in autumn (3.0°C; Fig. 3c). The value of T_{max} was highest at the station with the most urban elements in the surroundings (Mom). However, the most striking feature in Fig. 3a is the decreasing temperature with height. The value of T_{avg} was also highest in Mom, and shows the influence of station altitude, but that influence is not as strong as for T_{max}. The lowest median T_{min} was found in Dra, situated 207 m MSL, but low T_{min} is also found at the two lowest stations (Tre and Hei). In fact, as shown in the box plots, extremely low temperatures were found in Hei, which is situated close to the Rhine River. The warmest T_{min} is found in Nie at 169 m MSL although several other stations indicate similar or only slightly cooler T_{min} values. The highest T_{min} was also found in Mom in winter, but substantially higher T_{min} was found in Nie during spring, summer, and autumn. Large DTR was found at the stations near water (Tre and Hei), as well as at the station with most urban elements in the surroundings (Mom), while small DTR was found in the steeply sloping station (Nie) and at the hilltop station (Fig. 3d).

b. *Influence of elevation and relief*

The influence of elevation on station temperatures is shown in Table 2. The correlation between elevation and T_{max}, T_{avg}, and DTR was significant in all seasons and strongest during winter (up to 80% explained variance), but correlations between elevation and T_{min} were insignificant except for winter. The changes in T_{max} with elevation are greater than the dry-adiabatic lapse rate except in winter. This is probably a result of lower ventilation at lower (valley) locations than at higher (hilltop) locations. This suggests that elevation is an important driver for station T_{max} and T_{avg} but not for T_{min}. Since elevation affects T_{max} and T_{min} differently, elevation would also influence DTR. Elevation thus needs to be accounted for. To determine the influence of other properties in the surroundings, linear regression functions were used to remove the influence of elevation where significant (i.e., T_{max}, T_{avg}, and DTR but not for T_{min}). Measured as well as corrected yearly median T_{max}, T_{avg}, and DTR values are shown in Fig. 4. After correction for elevation, large station network $\Delta T_{max/avg/DTR}$ values of 1.5°, 0.8°, and 1.6°C, respectively, still remained. In the statistical analyses described in the next section, the corrected T_{max}, T_{avg}, and DTR values are used.

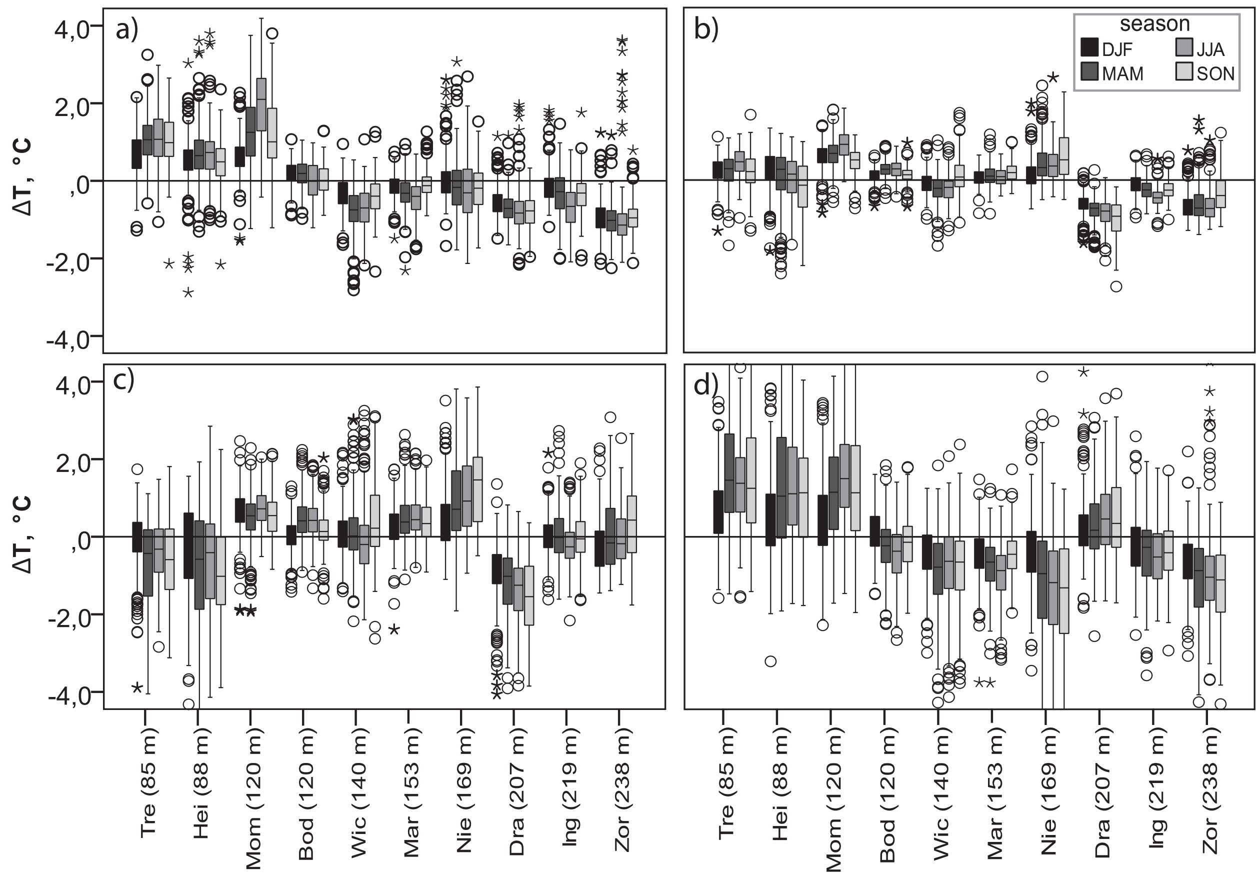

FIG. 3. Box plots of intra-station variability in the seasonal daily (a) T_{max}, (b) T_{avg}, (c) T_{min}, and (d) DTR for the 10 stations in the Mainz area [December–February (DJF), $n = 212$; March–May (MAM), $n = 187$; June–August (JJA), $n = 261$; and September–November (SON), $n = 182$]. Numbers in parentheses along the x axis following the station name are station elevation.

While the influence of elevation was limited for T_{min}, relief appears to be more important. One example is the apparent influence of low points in the terrain on temperature, as, for example, at Dra and Ing (6 km apart), located at similar elevations and in similar surroundings. Between these stations, the ΔT_{min} reached 1.5°C in autumn (Fig. 3c). Although both stations were located on generally gently sloping ground, the local relief differed where the colder station (Dra) was located in a hollow in the terrain while Ing was located on even ground. Low T_{min} was also found in the other station located in a low point of the terrain (Hei). Furthermore, the influence of slope appears to be important as the Nie station stood out with the highest T_{min} in spring, summer, and autumn (Fig. 3c). While the steepness of the slope generally ranged between 1° and 5°, the Nie station was located on a much steeper slope of 18° (Table 1).

c. *Importance of source radius*

To evaluate the importance of spatial scale on the population, built/paved area surface coverage, and night light intensity, these parameters were determined for the different radii (Table 3). The stations were then ranked in order of decreasing built/paved area surface coverage, population count, and night light intensity for each source radius (Fig. 5). The many changes in ranking between the distance classes indicate that the spatial scale matters when determining the station surroundings. Ranking changes are only minor between the 100- and 300-m radii but increase at 1000-m radius and are considerable for the 3000-m radius. However, low variability of the night-light-based rankings for the 100- and 300-m radii should be regarded with caution because of the low data resolution. Mom stands out as the only station with a ranking position unaffected by scale. The ranking position of Mar is also relatively robust, whereas the remaining stations show a high sensitivity to scale. The scale of the source radius is more influential in the rankings based on built/paved areas surface coverage and population (increases in radii caused changed ranks in 21 and 20 of 30 cases) in comparison with night light (10 of 30 cases, although part of this is likely due to low-resolution data).

TABLE 2. Regression functions and R^2 values between altitude and T_{max}, T_{avg}, T_{min}, and DTR. Correlations significant above the 0.1 level are in boldface; $N = 10$. Here, ** indicates that the correlation is significant at the 0.01 level (two tailed) and * indicates the same at the 0.05 level.

		Function for altitude	R^2
All data	T_{max}	$y = -0.011x + 1.66$	**0.69****
	T_{avg}	$y = -0.0066x + 1.02$	**0.63****
	T_{min}	$y = -0.0016x + 0.23$	0.02
	DTR	$y = -0.0095x + 1.43$	**0.41**
Winter	T_{max}	$y = -0.009x + 1.36$	**0.80****
	T_{avg}	$y = -0.0067x + 1.04$	**0.72****
	T_{min}	$y = -0.0047x + 0.76$	**0.43***
	DTR	$y = -0.0048x + 0.67$	**0.50***
Spring	T_{max}	$y = -0.0119x + 1.79$	**0.58***
	T_{avg}	$y = -0.0066x + 1.01$	**0.55***
	T_{min}	$y = 0.0007x - 0.13$	0.00
	DTR	$y = -0.0129x + 1.99$	**0.39**
Summer	T_{max}	$y = -0.0135x + 2.03$	**0.60****
	T_{avg}	$y = -0.008x + 1.22$	**0.64****
	T_{min}	$y = -0.0029x + 0.45$	0.06
	DTR	$y = -0.00114x + 1.70$	**0.34**
Autumn	T_{max}	$y = -0.0105x + 1.59$	**0.71****
	T_{avg}	$y = -0.0047x + 0.71$	**0.32**
	T_{min}	$y = 0.0022x - 0.36$	0.02
	DTR	$y = -0.0117x + 1.78$	**0.46***

The importance of scale is also visible in the R^2 values between station temperature (seasonal and total) and the examined parameters in the station surroundings (Fig. 6). Most of the T_{avg} and T_{max} and some of the T_{min} values correlated significantly ($p < 0.1$) with population, built/paved area surface coverage, and night light at 1000, 300, and 100 m, while the correlation for 3000 m was generally lower relative to the smaller-radii cases. DTR shows no significant correlation.

d. Land cover: Built/paved surfaces and vegetation

Of the 10 sites analyzed here, the station Mom, located in a residential area on the outskirts of Mainz, is characterized by the highest built/paved surface coverage in all distance classes (29%–40%; Table 3). At 3000-m radius, the agricultural sites all had some urban elements in their surroundings (8%–27% built/paved surfaces). For the smaller radii (100 and 300 m), Tre, Wic, and Ing had no built/paved surfaces while for example the two stations with sparsely built surroundings (Hei, Bod, and Mar) had 6%–17%.

The R^2 values between T_{max} and built/paved areas were highest at a radius of 1000 m (Fig. 6) during summer when this surface coverage corresponds to an explained variance of 49%. For influence on T_{avg}, no clear relation with source area radius was evident as significant correlations were found at all radii. The influence of built/paved areas on T_{min} was only significant in winter for the two smallest radii. The three stations with highest built/paved area surface coverage (Mom, Mar, and Bod) show high T_{min} values. However, substantially higher T_{min} was found in Nie in spring, summer, and autumn. The Nie station has no nearby buildings but is located on a very steep slope. DTR values show very little connection to the land cover. An independent-sample t test showed that the two main vegetation types (LCZ B or D; scattered trees or low plants; Table 1) present in the station surroundings had no significant influence on either T_{max}, T_{avg}, T_{min}, or DTR.

e. Population and night light intensity

Population varied substantially in the 100- and 300-m distances, where the larger apartment buildings near the station in Mom resulted in a considerably higher population compared to the agricultural stations. The variation was smaller for the larger radii. Night light intensity was also considerably higher in Mom at all radii. Both population and night light intensity correlate well with built/paved area surface

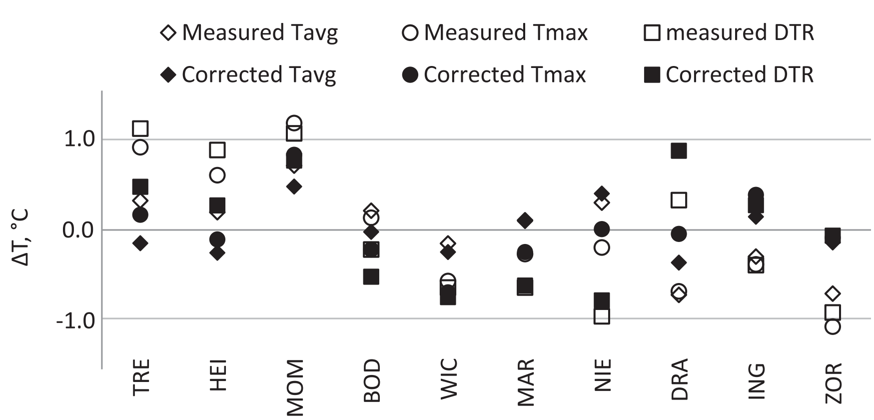

FIG. 4. Median values for overall ΔT_{max}, ΔT_{avg}, and ΔDTR based on measured data (open symbols) and data corrected for elevation differences (filled symbols) at the 10 stations.

TABLE 3. Properties of station surroundings: built/paved area (%), population (Pop; estimated number of inhabitants), and night light level [nW (cm^2 sr)$^{-1}$].

Station	100 m			300 m			1000 m			3000 m		
	Built/paved	Pop	Night light	Built/paved	Pop	Night light	Built/paved	Pop	Night light	Built/paved	Pop	Night light
Tre	0	0	0.6	2	6	0.7	1	50	0.7	13	20 000	1.7
Hei	7	3	1.8	3	48	1.9	8	1000	1.6	9	13 500	2.3
Mom	29	271	12.4	40	2450	12.4	36	14 000	15.5	39	62 500	16.5
Bod	17	21	1.9	17	176	1.9	13	3000	2.6	12	10 000	2.1
Wic	0	0	2.5	1	0	2.5	3	250	2.6	17	23 000	4.1
Mar	6	3	5.2	17	390	4.8	21	4200	8.8	27	41 000	6.7
Nie	1	0	4.5	3	0	3.8	15	5300	3.2	8	8500	1.5
Dra	2	0	4.3	9	3	4.3	15	3200	3.8	19	20 000	5.1
Ing	0	0	2	1	0	2	2	50	2.2	16	23 500	1.8
Zor	1	0	0.7	1	0	0.8	6	1000	1.1	15	18 000	2.1

coverage, particularly within the different radius classes (Table 4).

The covariation of temperature and population as well as night light intensity show similar patterns as built/paved area surface coverage, with R^2 values generally exceeding 0.3 for most T_{avg} and T_{max}, at the 100-, 300-, and 1000-m radii, and the highest level of explanation (69%) for population during summer (T_{avg}, 100 m; Fig. 6). Lower R^2 values were generally found for the 3000-m radii. The influence, especially on DTR, but also on T_{min}, was limited.

4. Discussion

A ranking of the 10 rural or semiurban stations in the Mainz area, based on the relative level of built/paved area surface coverage, population density, and night light levels, revealed considerable changes related to the size of the source radius (100, 300, 1000, and 3000 m). However, significant correlations between temperature and built/paved area surface coverage, population, as well as night light were found for all radii, but effects generally decreased considerably when considering the surroundings within the 3000-m radii. The consequences of this impact of scale will be discussed in the next paragraph, followed by the potential of using land cover, night light, and population data for assessing local temperature differences. Possibilities for using station metadata for assessing potential urban influence will be addressed in the following paragraph. As the examined parameters only explain at best around half of the variation in T_{avg} and T_{max}, and very little of the variation in T_{min} and DTR, the influence of relief and vegetation type on the remaining temperature residuals will be discussed in the final discussion paragraph.

The findings presented in this paper indicate that larger source radii, beyond 1000 m, are less suitable for assessing urban influences on station temperature readings, but in many studies of temperature trends, potential urban influence is classified based on the properties of the station surroundings on a scale of kilometers, for example, population in urban settlements near the stations (Peterson and Vose 1997; Gallo et al. 1999; Hansen et al. 1999; Ren et al. 2008; Das et al. 2011), or using information on larger-scale grids (Gallo and Owen 1999; Peterson et al. 1999; Hansen et al. 2001). As argued by Peterson and Owen (2005), low-resolution station location may prevent local and microscale analyses as, for example, the global station network used by Goddard Institute for Space Studies is provided with latitude and longitude data at 0.01° resolution, corresponding to a distance of about 1 km. Information related to LCLU within 500 m or less from the stations has been included for assessing the potential urban influence in temperature trend analyses but only on regional or country-scale studies (e.g., Fujibe 2009; Chow and Svoma 2011; Fall et al. 2011). Several urban climate studies showed that the immediate station surroundings, within 500 m, correlated closest with station temperature variations (Li and Roth 2007; Hart and Sailor 2009; Yokobori and Ohta 2009; Lindén 2011; Holmer et al. 2013). However, these studies focused on calm and clear weather conditions, when lower movements in the boundary layer air parcel limit the source areas. The present study indicates the importance of source areas within 100–1000 m when all weather situations are included, in agreement with Gallo et al. (1996), who found that LCLU within 100-m radius was more influential on DTR than LCLU within larger radii. While this and the above-mentioned studies indicate that the near-station surroundings are most influential for station temperatures, further studies would be needed to examine if the same applies to other regions and climate zones.

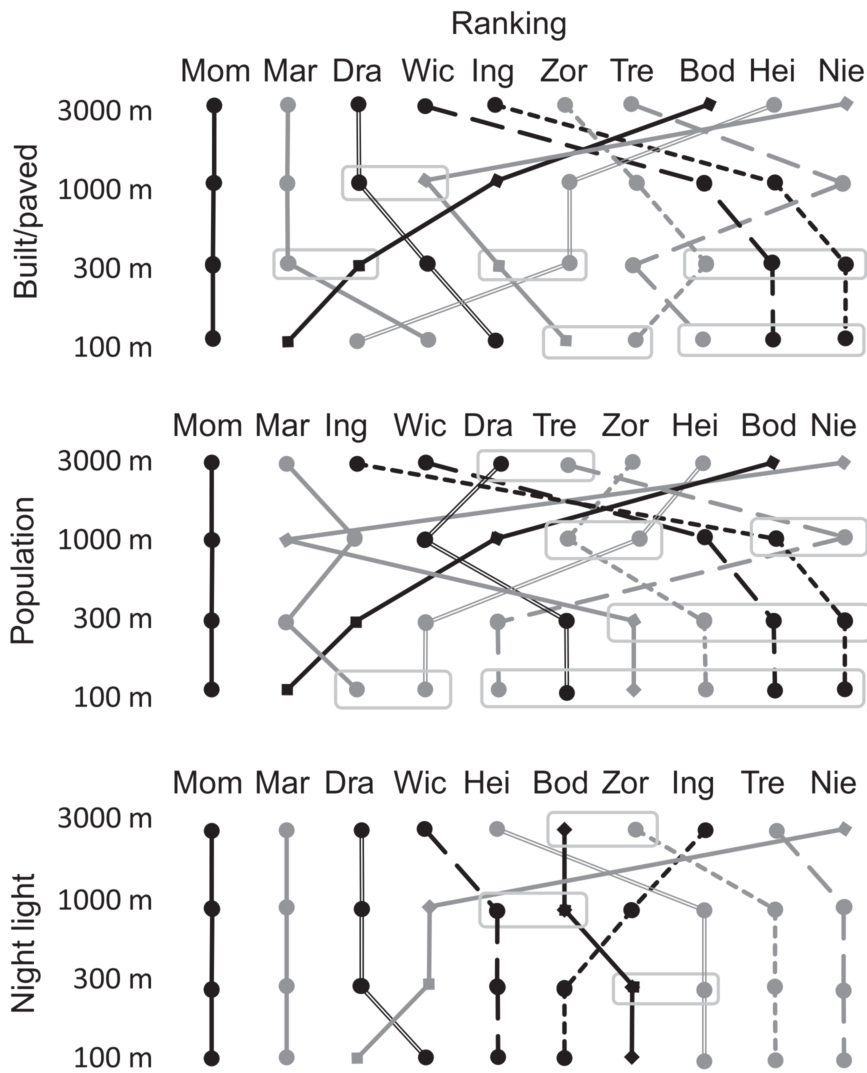

FIG. 5. Ranking of the stations according to (left to right) decreasing built/paved area surface coverage, population, and night light intensity within 3000-, 1000-, 300-, and 100-m distances from the stations. Stations that share a rank (parameter and scale) are enclosed in a gray rectangle. Night light ranking changes between 100- and 300-m radii should be regarded with caution because of the low data resolution.

In this paper, we find the highest levels of explanation for station network temperature when examining population and night light levels, and somewhat lower levels for built/paved area surface coverage. We also find that the three methods for characterizing station surroundings are highly correlated, indicating that population and night light are suitable proxies for built/paved area surface coverage. Both population and night light are often used as proxies for estimating the urban influence on temperature (Brown and DeGaetano 2010), and the correlation between near-station population, as well as night light, and temperature in this study indicates that they are both suitable proxies. Using population counts for determining urban influence has been questioned, however. For example, Jones et al. (2008) discuss the risks of using outdated population data in regions of rapid population growth. Night light intensity, at high resolution, has been suggested to be a better proxy for assessing the urban influence in temperature data (Hansen et al. 2010; Parker 2010). This study shows that population data, if of high resolution and updated, can be equally suitable for determining the potential urban influence at a station.

Metadata from meteorological stations are generally available for the near-station surroundings and the local environment (Aguilar et al. 2003). The importance of

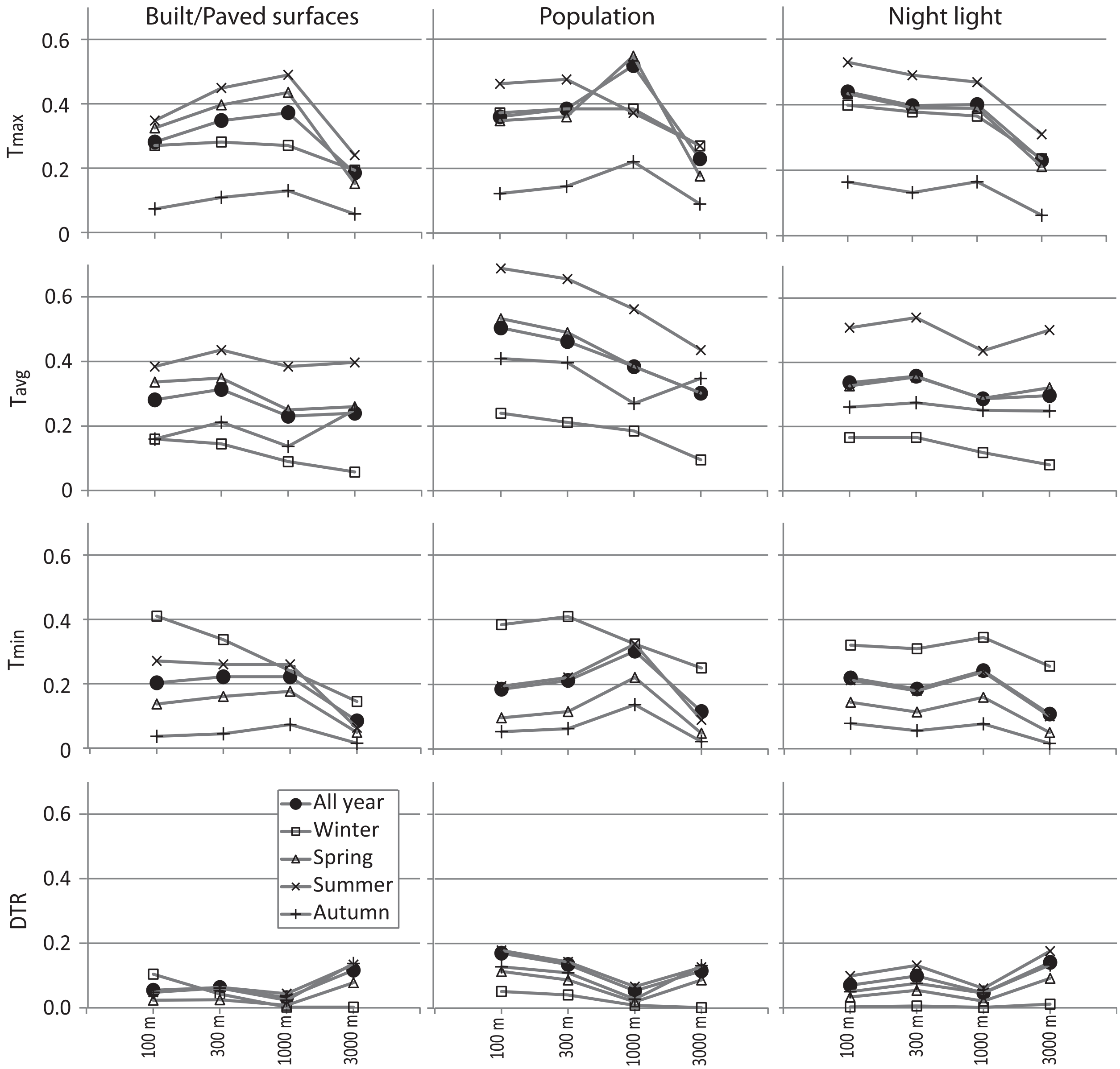

FIG. 6. Coefficient of determination R^2 between (top to bottom) T_{max}, T_{avg}, T_{min}, and DTR, and (left to right) , built/paved area surfaces, population, and night light intensity for the different radii. An $R^2 > 0.3$ value corresponds to a correlation significantly above $p = 0.1$, an $R^2 > 0.4$ corresponds to $p = 0.05$, and an $R^2 > 0.5$ corresponds to $p = 0.01$.

the near-station surroundings on temperature revealed in this study indicates that this metadata information can be used to estimate the relative contribution of specific properties of station surroundings and to assess their contributions to a UHI. However, for larger-scale analyses, individual assessments of station metadata may be too time consuming. Peterson and Owen (2005) excluded all urban influence on temperature at U.S. surface stations, by removing stations with more than 30 000 inhabitants within 6 km. Considering this rather rough classification scheme, most of the stations examined in this study would be removed as a result of their proximity to the city of Mainz and the surrounding villages. Also most of the longest European temperature records would be excluded, as they are located in or near the larger cities. For example, the four longest temperature records in Germany (>230 yr) are from Berlin, Karlsruhe, Frankfurt, and Munich and are all located in regions with high population densities ranging from 1700 to 4400 inhabitants per square kilometer (Statistisches Bundesamt, Germany; http://www-genesis.destatis.de, 2011). Excluding these stations, based simply on the high population

TABLE 4. Correlation (Pearson's) between built/paved area surface coverage, population, and level of night lights at the four different scales examined in this study; $N = 10$. Here, ** indicates that the correlation is significant at the 0.01 level (two tailed) and * indicates the same at the 0.05 level.

		100 m			300 m			1000 m			3000 m	
		Built/paved	Pop	Night light	Built/paved	Pop	Night light	Built/paved	Pop	Night light	Built/paved	Pop
100 m	Pop	0.87**										
	Night lights	0.75*	0.89**									
300 m	Built/paved	0.93**	0.89**	0.88**								
	Pop	0.87**	0.99**	0.91**	0.92**							
	Night lights	0.77**	0.91**	0.99**	0.89**	0.93**						
1000 m	Built/paved	0.81**	0.80**	0.93**	0.93**	0.85**	0.93**					
	Pop	0.83**	0.90**	0.96**	0.91**	0.92**	0.96**	0.96**				
	Night lights	0.77**	0.87**	0.96**	0.92**	0.93**	0.96**	0.93**	0.92**			
3000 m	Built/paved	0.65*	0.80**	0.85**	0.84**	0.86**	0.86**	0.77*	0.76*	0.93**		
	Pop	0.63	0.82**	0.83**	0.80**	0.88**	0.85**	0.73*	0.74*	0.92**	0.97**	
	Night lights	0.78**	0.92**	0.94**	0.90**	0.95**	0.96**	0.87**	0.89**	0.96**	0.93**	0.93**

densities, appears not to be desirable though, and using detailed meta-information of the immediate station surroundings could perhaps improve the assessment of urban influence of such long records.

Despite the spatially limited area and absence of dense urban structure among the stations examined in this study, temperature differences of on average 1.4°C (0.8°C when the influence of elevation was removed) were found, exceeding the larger-scale global warming signal of around 0.85°C since the late nineteenth century (Stocker et al. 2013). The temperature differences revealed here demonstrate a rural variability of similar magnitude to the UHIs of cities in this region, for example, Krefeld (Blankenstein and Kuttler 2004) and Trier (Junk et al. 2003). As only half of the variation in T_{avg} and T_{max}, and very little in T_{min} and DTR, can be explained by land cover, population, or night light, the origin of the remaining residuals will be discussed. Elevation impact follows the same pattern reported in Blandford et al. (2008). The effect is approximately twice as large in T_{max} compared to T_{avg}, and very limited in T_{min}, although the lapse rates identified here are much stronger compared to those found by Blandford et al. (2008). As the T_{max} lapse rate in Mainz exceeds the dry-adiabatic lapse rate of $1°C\,(100\,m)^{-1}$, this elevational signal is likely strengthened by generally less ventilated conditions at lower locations, allowing for a stronger heating compared to those at higher locations. The lack of elevational signal in T_{min} is likely caused by the strong influence of the general weather situation (*Großwetterlage*). If the weather is dominated by a high pressure cell over Europe, this will often lead to clear skies and weak winds. The result will be nighttime inversions and cold-air lakes in hollows and valleys. On the other hand, if a strong westerly airflow prevails, temperatures will decrease with height even in the valleys. Thus, T_{min} will be a blend of altitude influences that counteract each other, and although the properties of the station surroundings are very important also during the night, overall the effect on temperature is difficult to determine. High T_{min}s in our network are found at the three stations with built structure in the near surroundings, following the expected urban influence of prevented cooling (e.g., Trenberth et al. 2007; Brown and DeGaetano 2010). However, considerably higher T_{min} was found at the station located on a steeply sloping hill. Vegetation near this station is dominated by vertically oriented rows of vines, which may support a flow of colder air toward the bottom of the valley, thus limiting low T_{min}. Although slope at this station is within thresholds required for best-site classification according to the NOAA Site Information Handbook (NOAA/NESDIS 2002), T_{min} at this station appears to be substantially affected by this slope. The lowest T_{min} values were found in the two stations located in shallow hollows, likely supporting cold-air lakes, as was also described by Chung et al. (2006), thus further supporting the important influence of topography on T_{min}. The influence of built/paved area surfaces on T_{max} and T_{avg} is highest when the vegetation is most active (i.e., during spring and summer). This agrees with other studies that have shown vegetation to be important for temperatures (e.g., Bowler et al. 2010). However, the type of vegetation according to the LCZ classification did not impact station temperatures significantly, a result likely caused by the similarity of vegetation types among the investigated sites, as the fruit orchards trees were only slightly higher than the temperature instrument, thus allowing nocturnal radiative cooling and limiting a shading effect in the daytime. A moderating effect on temperature from shading of the higher trees surrounding the

Mom station does not seem likely as the station has T_{max} values that are among the highest, but perhaps the nearby trees contribute to diminished radiative cooling at night and thus the high T_{min}, although the effect is likely limited since the trees are scattered and a few meters away. Possible moderating effects of irrigation on temperature, as shown by Mahmood et al. (2004) and Lobell and Bonfils (2008), could not be revealed here because of a lack of information. Water is also well known to have a moderating effect on temperatures because of the high heat capacity (e.g., Oke 1987), but no moderating effect of water is found here as the two stations located nearest to the river have the largest DTRs. We thus conclude that the effect of a relatively small water body, such as the river in this study, on temperatures is very limited in extent and is not important in this case.

5. Conclusions

This study showed that the extent of the area used for determining the properties of the station surroundings for the assessment of potential urban influences at the station matters. Properties of land station surroundings within 1000 m covary with the temperatures at 10 stations in Mainz (Germany), but the correlation decreases at 3000-m radius. In our study area, station surroundings at source radii greater than 1000 m thus appear unsuitable for the assessment of urban influences on temperature readings. Detailed and updated information on near-station land use, or the equally suitable proxies, population and night light, should instead be used.

The temperature differences among rural and suburban stations indicate that rural variability is important. Variability in population and built/paved area surfaces explains only about half of the overall spatial variability among the stations, and our findings indicate that local topography is an important additional factor, particularly for T_{min}. Vegetation types had no significant effect on temperatures, although we recommend more detailed and weather-stratified studies, considering additional vegetation types, to further our understanding of the processes and factors influencing the temperatures at these stations.

Acknowledgements. We thank the agricultural meteorology service in Rheinland-Pfalz for providing the data and technical information about the weather stations, as well as three anonymous reviewers, who provided helpful remarks and suggestions for improving this manuscript.

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