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Determination of the urban heat island intensity in villages and its connection to land cover in three European climate zones

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ABSTRACT: Although urban heat islands (UHIs) have been found in many cities throughout the world, work on smaller settlements is still limited, especially concerning variations connected to climate zones. Meteorological stations are often regarded as rural when located in a village or small town, and any temperature bias is assumed negligible. In this paper, we therefore present air temperature variations and their connection to land cover in 3 European villages, boreal Haparanda, temperate Geisenheim, and Mediterranean Cazorla, all of them hosting long temperature records that might be biased. The villages were equipped with temperature sensors, and the surrounding areas were digitized to compare UHI effects and to evaluate the contribution of land cover on local cooling and warming. This sensor network reveals significant village UHIs in all 3 climate zones, with seasonal maximum intensities decreasing from north (1.4°C) to south (0.9°C). During summer, urban warming is most emphasized in minimum temperatures in boreal Haparanda and temperate Geisenheim but weakest in Mediterranean Cazorla, presumably because of limited plant transpiration due to high insolation and drought stress. Urban warming is correlated with building density in all 3 settlements and shows little seasonal variation. Even though the mountain river passing Cazorla substantially cools ambient temperatures at distances <100 m, mitigation of warming through water bodies is limited in the Central and Northern European sites. Our results suggest to treat rural instrumental station data with care and to avoid using data recorded in villages as unbiased reference records to adjust measurements from larger cities.

KEY WORDS: Urban climate · Urban heat island · Village microclimates · Land cover · Rural stations

1. INTRODUCTION

An alteration of the landscape eventuates in a change of local climatology detectable in various meteorological parameters. The urbanization of an area is one example for such a conversion, implying a gradual replacement of vegetation and bare soil by buildings and paved surfaces. Among other implications, urbanization increases temperatures and leads to the establishment of an urban heat island (UHI) if compared to the rural surroundings (e.g. Landsberg 1981, Oke 1987). This difference is usually strongest in summer and at night (Oke 1982, Morris et al. 2001). Arnfield (2003) summarized several important factors influencing urban temperatures positively including reduced evapotranspiration as a result of sealed surfaces and missing vegetation, a lowered exchange of air masses, and increased multiple reflection and radiative heating due to urban structures and anthropogenic heat release. Because of the heterogeneity of the urban landscape, climate varies within a city (Unger 2004, Thorsson et al. 2011), and UHI intensity (UHII) is affected by factors such as regional climate or adaption strategies as well. Rapid urbanization has been connected to an increased UHI (Chen et al. 2006), and this urban warming has

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been found to be positively correlated with population density (Steeneveld et al. 2011). UHI studies were primarily focused on larger cities, e.g. Nanjing, (Huang et al. 2008), Thessaloniki (Kantzioura et al. 2012), Bejing (Zhao et al. 2011), or Melbourne (Morris et al. 2001). However, smaller settlements with a population of ≤10 000 inhabitants have been linked to increased urban temperatures as well (e.g. Torok et al. 2001, Hinkel et al. 2003).

Because the microclimate of a location is strongly influenced by its surroundings, meteorological stations should be placed with great care to be representative for a region (Aguilar et al. 2003). In an urban area, this implies regarding the occurrence of nearby structures such as buildings, streets, and trees as factors that alter radiation, humidity, and wind patterns. Accordingly, a strong relation was detected between temperatures measured in cities and the surrounding land cover (e.g. Lo & Quattrochi 2003, Chen et al. 2006), an issue that still needs to be assessed for smaller settlements as well.

The assessment of urban temperatures is of high importance, not only with regard to human comfort and well-being (Mayer & Höppe 1987) but also concerning representative temperature measurements for specific regions. The anthropogenic influence on climate alters temperature trends (Jones & Wigley 2010), thereby adding critical information to the interpretation of 20th century global warming. Even though Parker (2010) considered the UHI effect on temperature trends to be small, Hansen et al. (2001) and Ren et al. (2008) detected a significant impact in the US and Chinese networks, respectively. Therefore, approaches to homogenize temperature data have become vital to ensure their reliability (Brunet et al. 2006, Venema et al. 2012). Albeit aiming at removing all non-climatic impact in the temperature data, homogenization and correction of time series might as well have inadvertent implications, like the recovery of urban warming bias (Zhang et al. 2014, Dienst et al. 2017), emphasizing the need to adjust records with special diligence. Cities contain the highest potential to affect the representativity of meteorological station measurements due to their large extension, but even smaller towns and villages influence the observations. Since studies vary vastly with respect to measurement periods, instrumentation, and data selection, there is need to establish a suitable dataset for different villages in varying climate zones.

The aim of this study is to assess the impact of land cover on urban air temperatures in 3 smaller settlements in Sweden (boreal Northern Europe), Germany (temperate Central Europe), and Spain (Mediterranean Southern Europe). Previous work confirmed the existence of a UHI in the Swedish and the German villages (Lindén et al. 2015b), which we here compare with the newly assessed Spanish village. The main goal of this study is to analyze which land covers contribute most to warming and cooling and whether the impact is different in the various climate zones.

2. STUDY SITES AND METHODS

2.1. Study sites

The study sites are located in Haparanda in northern Sweden near the Arctic Circle, Geisenheim in western Germany in the temperate zone, and Cazorla in southern Spain in the Mediterranean (Fig. 1). We refer to these settlements as villages considering the widely applied population threshold of <10 000 inhabitants as utilized by the KNMI Climate Explorer introduced by Trouet & Van Oldenborgh (2013) and the Global Historical Climatological Network (Peterson & Vose 1997, Hansen et al. 2001). While this criterion separates the study sites from towns and cities, we want to emphasize that Haparanda, Geisenheim, and Cazorla are nonetheless urban areas, as a settlement with several thousand inhabitants implies substantial built-up areas, infrastructure, traffic, etc. The term urban is therefore used in this paper especially to acknowledge the dominant land cover (streets, buildings, paved surfaces). Haparanda and Geisenheim gained town privileges in the past and are administratively considered as towns in Sweden and Germany, respectively.

Cazorla is situated at the western border of the Sierras de Cazorla natural park in southeastern Spain and has a population size of about 8000. The climate is temperate with dry and hot summers, characterized by mean temperatures exceeding 22°C at least in one month of a year (Köppen & Geiger: Csa; Kottek et al. 2006). Since the village is located on a mountainside in hilly terrain, it extends from 720 to 900 m above sea level (a.s.l.). The small river Cerezuelo (width ~10 m) originates in the nearby mountain range and runs through the settlement. The building pattern is homogeneous, with light-coloured buildings of 2 to 3 storeys and small streets. Bare rock and forests surround Cazorla to the east and south, whereas to the north and west, olive plantations dominate the landscape.

Geisenheim is located in central Germany on the eastern banks of the river Rhine (width ~400 m) and south of the Taunus mountain ridge. The village stretches along the hillside, resulting in a height difference of 55 m from the river (80 m a.s.l.) to the topmost point (135 m a.s.l.). Characterized by fully humid, temperate climate with warm summers (Köppen & Geiger: Cfb), the region is dominated by agriculture, especially wine growing. Geisenheim consists of an old and dense medieval centre with timber-framed one-storey houses and small streets, surrounded by residential areas with 1 to 3 storey buildings. Today, although the Geisenheim administrative region is home to ~11 500 people, the village as such has ~7500 inhabitants.

Haparanda is situated in northern Sweden on the border with Finland, and its climate is dominated by fully humid conditions characterized by ample snow and cool summers (Köppen & Geiger: Dfc). The village is situated north of the Baltic Sea, with the river

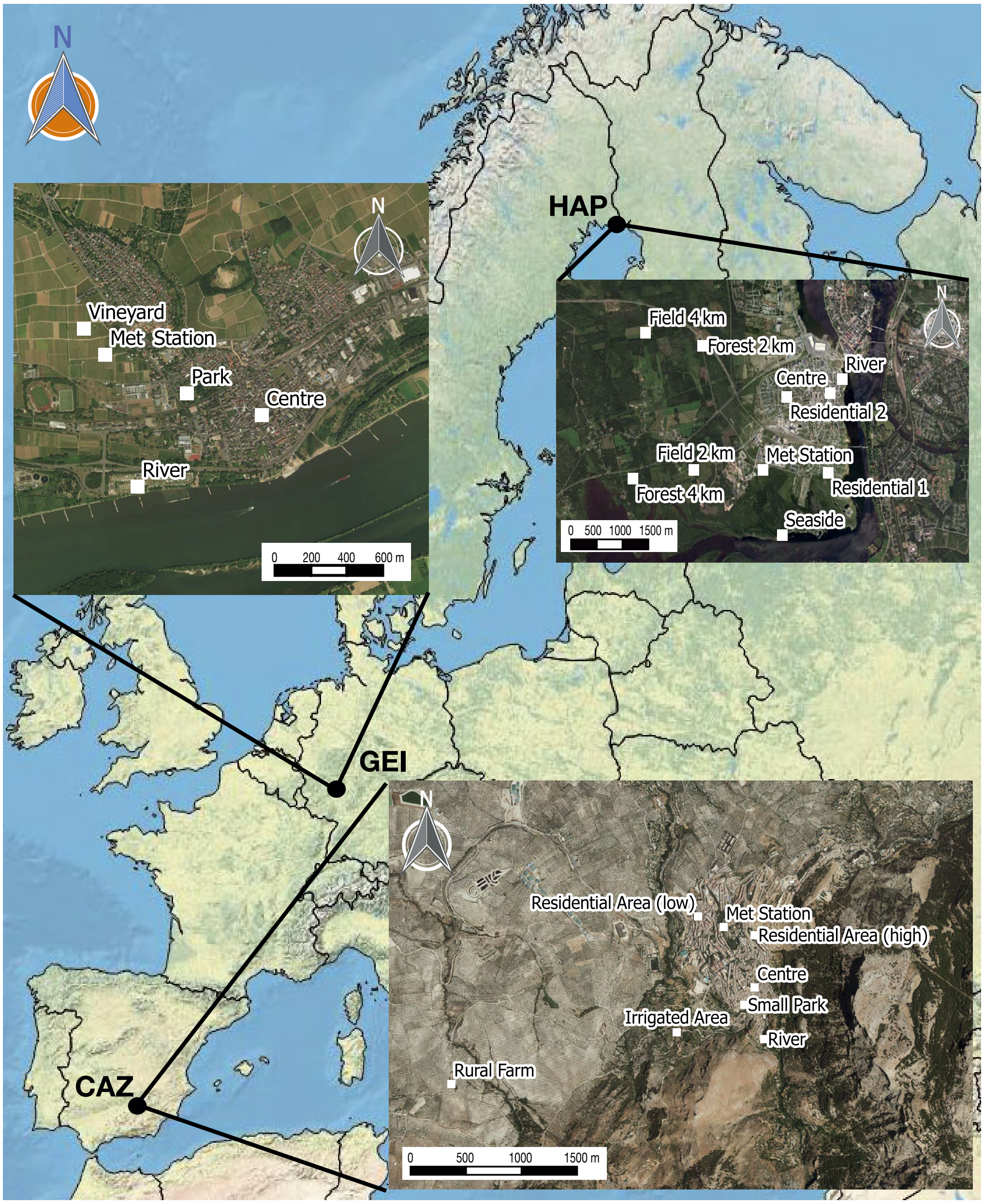

Fig. 1. Sensor setup in the 3 villages. The white squares indicate the sensor locations. Satellite images for Geisenheim and Haparanda have been derived from Microsoft® Bing maps 2017 (accessed on 03/2017) and for Cazorla from ESRI map services 2017 (accessed on 04/2017). CAZ: Cazorla; GEI: Geisenheim; HAP: Haparanda; Met Station: meteorological station

Torneo (width ~350 m) running to its eastern side entering the nearby sea. The surrounding landscape is flat and close to sea level, and is primarily covered by forests and some meadows. A square forms the centre of Haparanda, with mostly old wooden buildings in its vicinity. Residential areas mainly consisting of wooden one-storey houses have been constructed to the west and south of the centre and are home to ~7000 inhabitants. The building pattern is rather loose, including widely spaced streets even in the centre. Small industrial areas are found north and southwest of the village.

2.2. Temperature sensor network

A network of temperature sensors was established in each village and its surroundings (Fig. 1), originally to detect the urban warming effect on historical temperature measurements (Lindén et al. 2015b, Dienst et al. 2017). We closely followed the WMO guidelines for sensor installation in urban climate studies (WMO 2008), though a completely standardized placement, e.g. on unified posts, was not feasible because of the complexity of the sites, nearby urban structures, and human activity. Nevertheless, all sensors were placed inside a protection against insolation at 2.5 m height above the ground, usually on existing posts or trees as detailed in Table 1. All sensors were installed so that a free air flow is guaranteed, no walls or buildings are too close, and placement is north facing to avoid direct solar radiation. Each sensor was placed in a different microenvironment to support a good comparison regarding the impact of varying land cover. The villages were endued with a core set of air temperature sensors covered by radiation shields and additionally measure relative humidity (HOBO Pro v2 U23-001 in radiation shield RS1, Onset Computer). During a 3 wk intersensor comparison, considering 10 min measurement intervals, differences were <0.05°C on average, including <5% of values exceeding a difference of 0.1°C, and could therefore be ignored in the analysis.

In each village, 1 sensor was established in the centre and 1 outside the urban area to assess the UHI magnitude. Since villages in general are often located at rivers or streams like the ones investigated here, another core sensor was placed at the riverside. In Haparanda and Cazorla, additional smaller air temperature sensors (HOBO TidbiT v2 data logger, Onset Computer) were installed to increase coverage of the varying surroundings and topography, since the areas are more diverse than in Geisenheim with mostly cropland and the river surrounding the village. These smaller sensors were equipped with a white plastic cover and placed on the shaded northern side of trees to minimize the impact of direct insolation. The common measurement period started in September 2015 and lasted 1 yr. The sensors were set to measure in 30 min intervals to achieve a high temporal resolution. In total, 5 U23 sensors were installed in Geisenheim and Haparanda and 3 in Cazorla. In addition, 5 TidbiT sensors were installed in Haparanda and 5 in Cazorla (see Table 1).

2.3. Digitization

To assess the influence of land cover on air temperatures, the surroundings of each temperature sensor were manually digitized based on satellite images (Microsoft® Bing maps 2017, ESRI map services 2017) using the open source GIS software QGIS (QGIS Development Team 2017) to achieve the best results possible in terms of accuracy and spatial resolution (up to 0.2 m pixel^{-1}). Five categories were introduced to account for different types of land cover found in the 3 study areas: buildings, impervious surfaces, vegetation, water bodies, and bare soil/gravel/sand. The type of natural vegetation as well as crops grown varies because of different climatic conditions and cultivation practices. High vegetation implies dense conifer forests in Haparanda and dense woodland in Geisenheim, whereas in Cazorla, it refers to open evergreen forests of limited height. As stated in Section 2.1., cultivated areas are dominated by wine growing in Geisenheim and are more or less limited to olive plantations in Cazorla, while Haparanda has no cropland at all. Low vegetation refers to mainly grassland and bushes in all 3 villages. Since a distinction is not always possible using satellite photography, and there are no clear definitions for different vegetation types, all were combined in the category vegetation.

Other studies have demonstrated the immediate surrounding up to a distance of 1000 m to the measurement site to be influential (e.g. Li & Roth 2009, Lindén et al. 2015a), and considering these findings, land cover was digitized in 50, 100, 500, and 1000 m distances to the sensors. For each sensor and radius, the area covered by 1 single type of land cover within a certain radius was compared to the total area covered by all types within this radius, thus providing the proportion of 1 land cover type within a defined radius. These values were later used for the correlation and regression analysis including all sensors and radii.

Table 1. Overview of the different sensors positioned in every village

Location	Sensor	Site description	Elevation (m)
Haparanda (Sweden)			
Village centre	U23	On lamp post on lawn; small wooden buildings and some vegetation around; paved streets	5
River	U23	On lamp post on lawn; next to riverside; grass surrounding spot; greater buildings in some distance	2
Residential area 1	U23	On old meteorological station post in garden with lawns and small wooden houses	4
Residential area 2	U23	On tree in backyard with lawns and small wooden houses	10
Meteorological station	U23	On gate of automatic weather station; outside city (about 200 m away from buildings); on grass/gravel next to forest	9
Seashore	TidbiT	On tree 15 m away from sea; wet ground; forest/bushy area	1
Field 2 km	TidbiT	On small tree in ditch with some more trees between fields with high grass; 1 km away from sea	8
Field 4 km	TidbiT	On small tree in ditch with some more trees between fields with high grass; 4 km away from sea	10
Forest 2 km	TidbiT	On tree in forest; widely spaced large trees; bushes and tall grass in openings; 3 km away from sea	10
Forest 4 km	TidbiT	On tree in forest; widely spaced large trees; bushes and tall grass in openings; 0.5 km away from sea	4
Geisenheim (Germany)			
Village centre	U23	On lamp post near camping site; lawn and gravel paths with some trees; 30 m away from river	93
River	U23	On lamp post in town centre square; paved ground; square is surrounded by buildings made of stone	84
Park	U23	On tree in the park of the University of Applied Sciences; lawn and trees; parking lot/street nearby	101
Vineyard	U23	On post in the vineyards outside the town; vine branches; smaller paths nearby	120
Meteorological station	U23	On fence of official automatic weather station in the vineyards outside town; lawn; paths and vine branches nearby	110
Cazorla (Spain)			
Village centre	U23	On balcony in narrow street with 3 storey buildings; streets and similar buildings nearby	823
River	U23	On post in garden of a house next to the river; grass; bushes and trees next to river; few houses	818
Rural farmhouse	U23	On tree of rural farmhouse; olive plantations around	823
Small park	TidbiT	On tree in bushes; next to parking lot	785
Meteorological station	TidbiT	Within the screen of the meteorological station; gravel; 1 or 2 storey buildings around	813
Irrigated area	TidbiT	On tree in irrigated plant area	843
Residential area (low)	TidbiT	On tree in small open area in middle of residential area; 1 or 2 storey buildings; some trees	742
Residential area (high)	TidbiT	On tree in small open area in middle of residential area; 1 or 2 storey buildings; some trees	853

2.4. Data analysis

For each sensor, 48 measurements d^{-1} over 365 d were available to evaluate daily mean, minimum, and maximum air temperature (TM, TN, and TX, respectively). Even though the setup allows for very high temporal resolution and robust daily means, the actual minimum and maximum temperatures could not be estimated, as the recorded values likely occurred in between the measurement intervals. A height correction was not applied to the data, since differences in elevation are either small (Haparanda, Geisenheim) or topography is complex (Cazorla) so that a correction might as well amplify differences caused by elevation, especially regarding TN. The data were used to calculate daily, monthly, and seasonal values. Since the main goal of this study is to assess the impact of land cover on temperatures, seasonal temperatures were correlated against different land covers surrounding the sensors and, a 2-tailed *t*-test was performed to estimate significance ($p < 0.10$). A subset of data was used in a regression analysis to estimate the temperature change per unit land cover change.

Most of the TidbiT sensors installed proved to be biased by direct solar radiation, revealing that the white plastic coverage, and north-exposed placement was insufficient to prevent this bias. While data in Sweden are insignificantly influenced mostly because of shading by other vegetation, several sensors in Cazorla display a strong impact. Since an approach to correct the biased data might overly alter the site-specific differences, daytime data were disregarded from analysis, and only the properly shielded core measurements (centre, rural reference, river) were used. To support spatial coverage in the correlation and regression analyses, additional data were exclusively selected from measurements of TN and hence are not biased.

3. RESULTS

3.1. Spatial temperature patterns

To assess the possible formation of a UHI and the effect of nearby rivers in the 3 European climate zones, spatial differences in seasonal TN and TM were analyzed. In each village, a subset of 3 fully protected U23 sensors representing urban, rural, and riverside locations was used for comparison. Fig. 2 reveals the existence of a UHI in every village with the general pattern of spatial differences in TM being persistent throughout the seasons, though at varying magnitudes. The urban–rural temperature patterns are similar in Haparanda and Geisenheim,

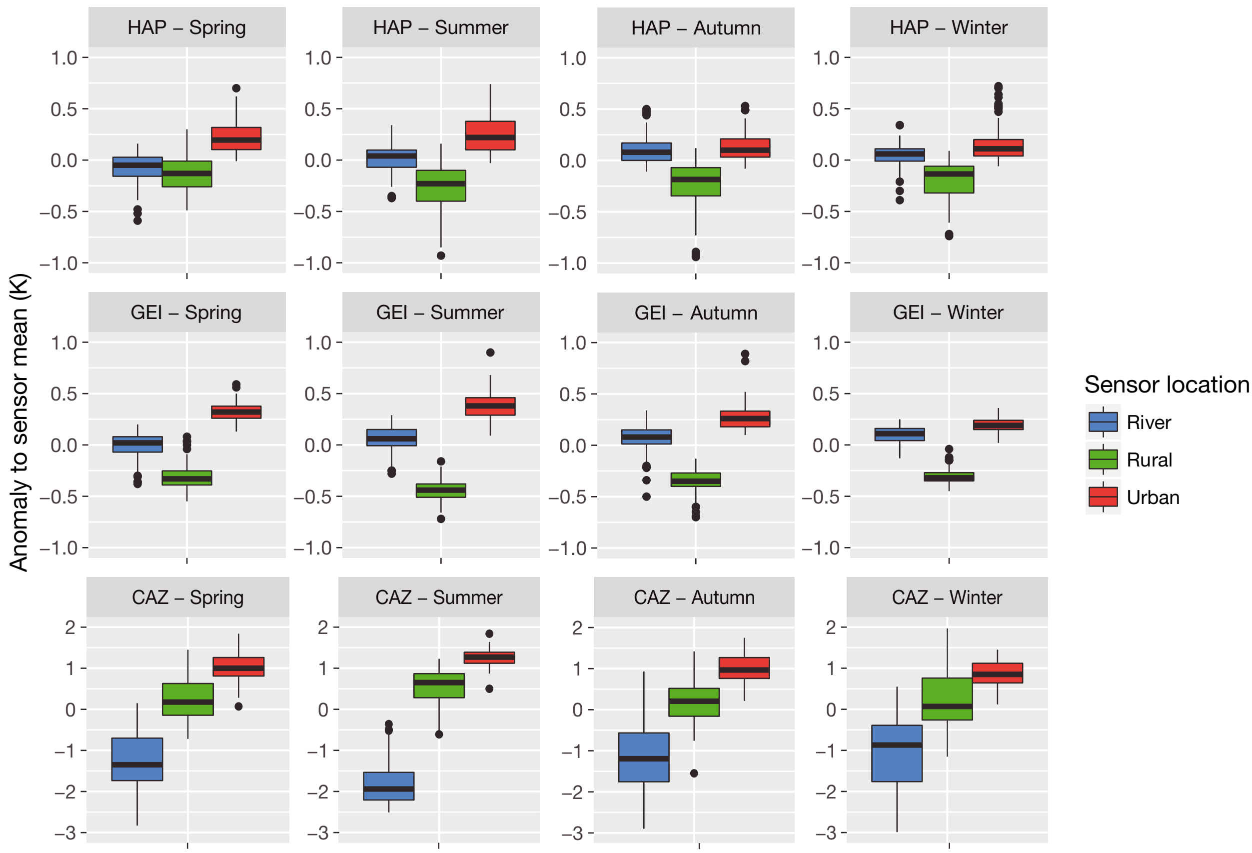

Fig. 2. Seasonal mean temperature values for river, centre, and rural U23 sensors in each village. Temperatures are shown as differences to the mean of all sensors. Boxplots display the median (black middle line), the upper and lower quartile including 50% of the data (coloured box), and whiskers (vertical lines) including the other 50%. If a value lies beyond 1.5 times the interquartile range, it is plotted as an outlier and excluded from the whiskers, reducing the amount of data within. CAZ: Cazorla; GEI: Geisenheim; HAP: Haparanda

whereas Cazorla displays a different pattern. The median difference is largest during summer in Geisenheim (0.8°C) and Haparanda (0.5°C) and smallest during winter, reaching 0.5 and 0.3°C, respectively. In both villages, the river site remains cooler than the urban site but is still warmer than the rural site. This pattern is most pronounced in summer and spring. In Cazorla, the urban site is also the warmest, with smallest differences in summer (0.6°C) and larger differences in all other seasons (~0.8°C). In addition, the location next to the river is cooler than both the urban and rural site, especially in summer (−3.2°C in comparison to the centre).

Patterns in TN are very similar to TM, although differences are more distinct and variable in TN (Fig. 3). Regarding the UHII, Haparanda centre shows a warming of 0.4°C in winter and 1.4°C in summer. In Geisenheim, the magnitude is larger in winter (0.6°C) but slightly smaller in summer (1.1°C). Cooler temperatures at the riverside when compared to the centre are present in TN as well, which is especially true for spring but not for summer in Haparanda, when both locations show the same temperature values. The Cazorla river site is substantially cooler if TN is considered, exceeding even −4°C in summer relative to the centre, whereas the rural–urban difference is stronger in the colder seasons (~0.9°C), just like in TM.

3.2. Correlation of land cover and temperatures

To analyze the influence of land cover on local temperatures, a regression analysis was performed between the sensor measurements (TN of each season) and the land cover considering different radii. This analysis indicates complex associations, including smaller variations among seasons but stronger ones among the villages in the different climate zones. Strong correlations between temperature and water bodies are recorded in Cazorla and even more so in Haparanda and Geisenheim if buildings or vegetation are considered instead of water. Fig. 4 shows the coefficients of determination for TN for the most important land cover classes. A significant warming influence of buildings on minimum temperatures is recorded in Geisenheim and Haparanda, particularly for the smallest radii (<100 m) in Geisenheim (R^2 >

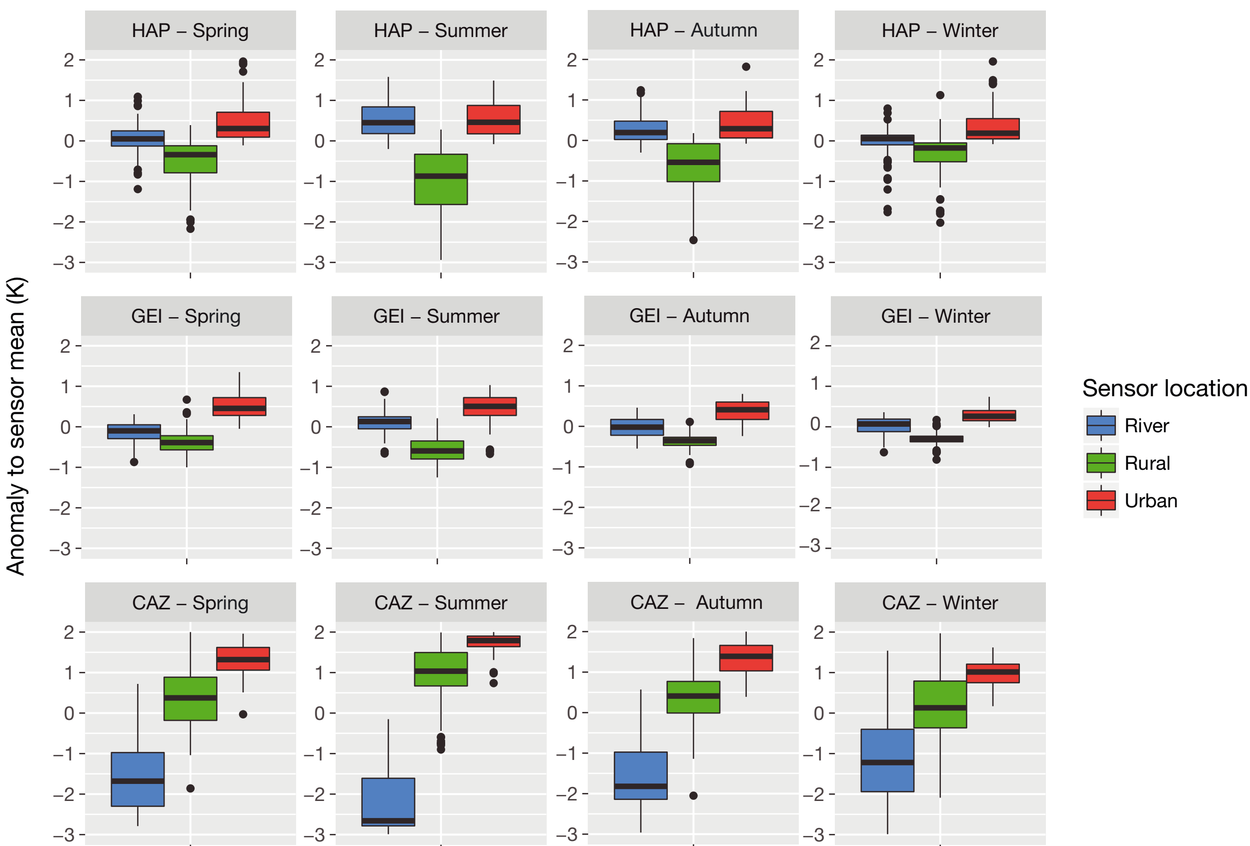

Fig. 3. Same as Fig. 2, but for seasonal minimum temperature values

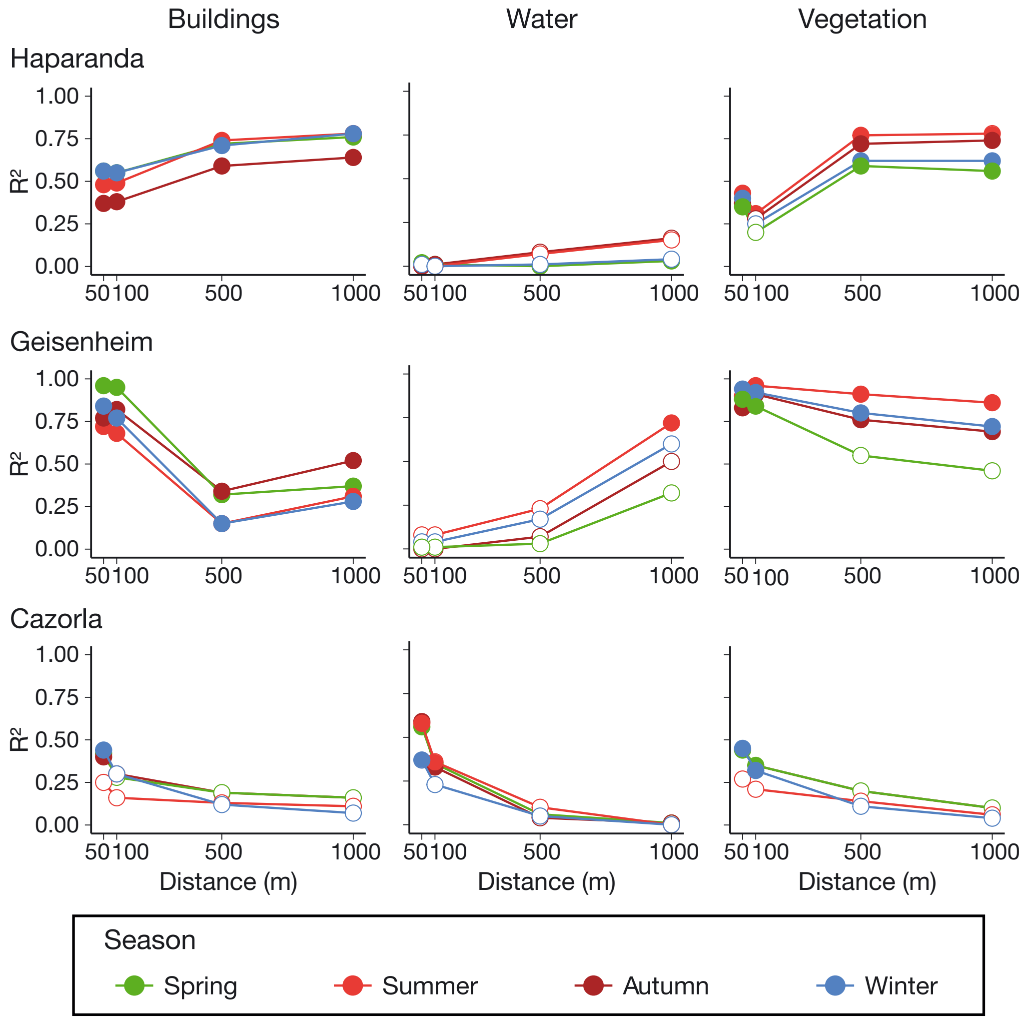

Fig. 4. Coefficients of determination shown for 3 different types of land cover in each village. Seasonal temperatures were correlated with the specific land cover in 4 different radii. Filled dots indicate significant correlations on a 90% level

0.7 for all seasons), whereas in Haparanda, the 500 and 1000 m radii reveal highest coefficients ($R^2 > 0.5$ for all seasons). Even though buildings have no distinct impact on TN in Cazorla, except for the closest radius of 50 m, water bodies do. Spring, summer, and autumn temperatures are negatively correlated with water bodies in up to 100 m proximity, but the relation decreases with distance. An inverse pattern is revealed in the 2 other villages. Whereas in Haparanda the coefficients of determination increase with distance, though on an overall low level, the values are higher in Geisenheim, particularly in the 1 km radius and during summer ($R^2 = 0.72$). Summer temperatures in Haparanda are (negatively) influenced by vegetation, which is most prominent in 500 to 1000 m radii. In Geisenheim, the pattern is reversed, since the correlations are strongest for the close surroundings and decrease with distance. The same is true for Cazorla, where significant relations were recorded up to a distance of 100 m. During summer, temperatures are neither significantly correlated with vegetation nor with buildings.

Although other findings are not shown, both other types of land cover need mentioning in addition to the results displayed in Fig. 4. Impervious surfaces cause warming in all villages, particularly in Haparanda ($R^2 \approx 0.7$). These patterns are similar to the ones detected for the building land cover and merely confirm the uniform performance of urban surfaces. The bare soil/sand/gravel land cover is negligible in terms of its occurrence within the digitized radii if compared to the other types of land cover, particularly in Haparanda and Geisenheim. The poor correlation results might simply be caused by this circumstance, and a reliable statement on how temperatures could be affected is not possible.

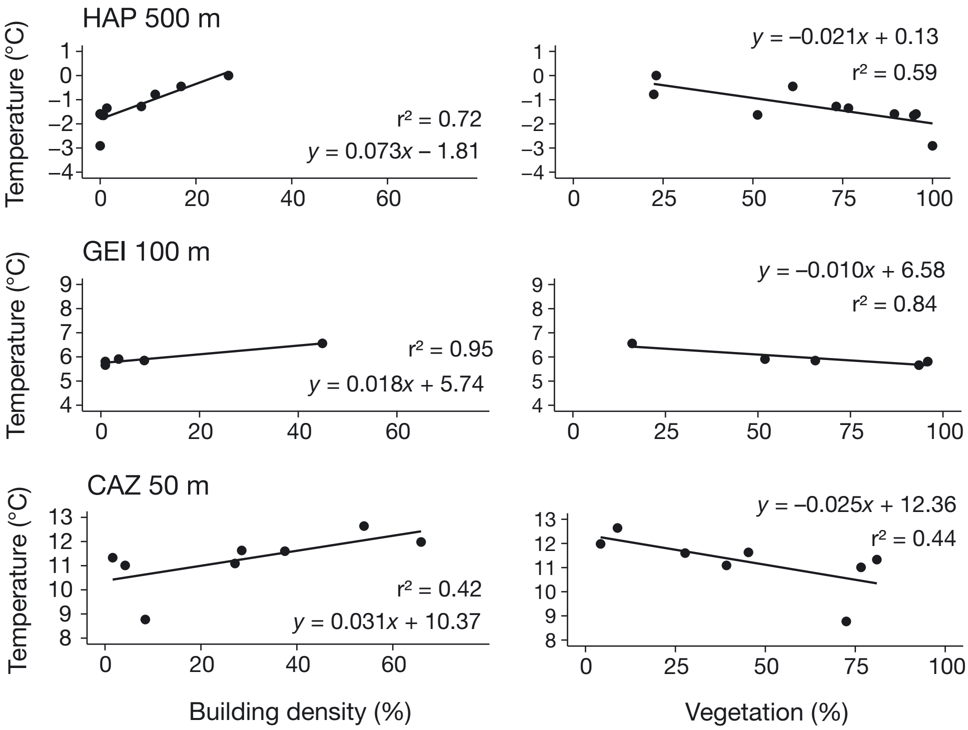

Fig. 5. Regression analysis for selected types of land cover in a specific radius which revealed strong and significant ($p < 0.1$) correlations with temperature. The equations display the rise or decrease in temperature per percent increase in type of land cover. CAZ: Cazorla; GEI: Geisenheim; HAP: Haparanda

3.3. Regression analysis

Several of the significant correlations have been selected and are shown as a regression analysis in Fig. 5 to estimate the degree of warming and cooling in association with land cover. We here focus on minimum spring temperatures to increase comparability among the sites. The analysis includes the dominant warming caused by buildings in all villages as well as the dominant cooling related to vegetation, even though water had a significant impact as well in the Mediterranean village. In a radius of 500 m, spring TN in Haparanda is considerably lowered if the area is covered with high vegetation (−0.2°C per 10% land cover increase). An even stronger but inverse trend is recorded for building density, even if building density is less than 30%. The 100 m radius pattern in Geisenheim is quite similar to that in Haparanda, although the rates of warming (0.2°C per 10% buildings) and cooling (−0.1°C per 10% vegetated area) are lower. While vegetation cover is generally well distributed, building density is below 20% for all locations but one, possibly limiting the reliability of the indicated trend. However, building density is more evenly distributed for other radii, and the relation with temperatures remains similar, substantiating the validity of this result. In Cazorla, the cooling caused by vegetation reaches −0.3°C per 10% land cover increase in a radius of 50 m. For the same radius, a smaller but positive trend is revealed by correlating building density and spring temperatures, demonstrating a warming influence similar to the other 2 villages. All regression analyses displayed in Fig. 5 are statistically significant at $p < 0.1$.

4. DISCUSSION

The results of this study showed that villages in Sweden, Germany, and Spain develop a substantial UHI with regard to size as well as building pattern of the urban areas considered and that maximum UHII weakens from north to south, as previously presented by Wienert & Kuttler (2005). The UHI persists throughout all seasons, and building density contributed most to the warming. Vegetation provides significant cooling in all villages but is less prominent in Cazorla, where water is most influential. Here, we first discuss the influence of topography and sensor setup on the temperature network. We then address the seasonal UHI course in the villages in Northern, Central, and Southern Europe and compare our findings with other studies. Last, we address the similarities and differences in the relation between land cover and temperatures in the 3 different European climate zones.

4.1. Topography

Topography is a minor factor in Geisenheim and especially in Haparanda but is an important one in Mediterranean Cazorla. Cazorla is situated in a mountainous region, and the differences in height between the sensors reach up to 100 m. Assessing influences due to topography remains complicated, particularly for TN. For instance, the steepness of a slope has an impact on how deep surface-induced cooling penetrates into the atmospheric layer (Jarvis & Stuart 2001). Particularly on clear, calm days, west-exposed mountain slopes are expected to become warmer during daytime, whereas at night, they cool faster and a downhill wind establishes, cooling the village further down the slope (e.g. Barry 2008, Poulos & Zhong 2008). This likely mitigates UHI in Cazorla, particularly in TN.

Consequently, the data were not adjusted for elevation, as an adequate correction would need to be based on a precise understanding of the local climatology and might otherwise alter site-specific differences and even increase biases. Even though sensors were placed at different elevations in Cazorla, no distinct warming or cooling patterns associated with topography were found that could be used for correction purposes. This might be because the landscape continues to slope westbound and no real valley situation is present. Nevertheless, in the complex terrain of Cazorla, temperatures are less dependent on surrounding land cover. This situation is further complicated by shading effects caused by the nearby mountains in the east. Sunlight reaches the rural areas earlier, thereby shifting the diurnal curve in comparison to the village sensors which are shaded by the mountains for a longer time, e.g. during summer, there is a 1.5 h delay in the centre. Since only TN has been used, data are not influenced by shading patterns.

Although the dataset from Cazorla contains uncertainties due to topography, 6 of 8 sensors are located within an altitudinal range of <50 m, and the core sensors (centre, river, rural farmhouse) are all placed at the same elevation. Furthermore, since the analysis is based on seasonal median temperatures, specific meteorological features only have minor effects on the data.

In general, cloudiness reduces spatial variations and is often linked to higher wind speeds that have similar mitigating effects on UHII (e.g. Unger 1996, Kim & Baik 2002). Inversions might also alter the altitudinal patterns. Influences like these should be negligible, though, since the analyses performed here to detect spatial warming and cooling patterns are not based on selected days but can be regarded as an all-weather approach including all data available, allowing for a robust estimation of urban warming.

4.2. Village UHIs

The 3 sheltered core sensors (centre, river, rural farmhouse) allow for a good comparison even in Cazorla, as these were placed at the same elevation. In Haparanda and Geisenheim, UHII was highest in summer minimum temperatures in agreement with other studies summarized by Arnfield (2003), reaching 1.4 and 1.1°C, respectively. UHII is generally lower in the villages assessed here compared to studies in larger cities; Kłysik & Fortuniak (1999) report nighttime UHII during summer to reach 3 to 4°C in Lodz (700 000 inhabitants), and Bottyán et al. (2005) document a mean maximum intensity of 2.5°C in Debrecen (200 000 inhabitants) during the non-heating season. However, given the relatively low population density, low building density, and size of the villages, the additional warming amounting to up to half of the warming in the cities studied by Kłysik & Fortuniak (1999) and Bottyán et al. (2005) is to be characterized as a substantial change in local climate. In addition, our study presents seasonal median minimum temperatures including all weather conditions. An investigation on maximum UHII, considering a selection of clear sky conditions and calm days, would naturally reveal greater urban–rural discrepancies. Nevertheless, the values reported here confirm an increase in UHII in line with urban growth as noted elsewhere (Torok et al. 2001, Chen et al. 2006, Szegedi et al. 2013). Our study thereby adds information at the lower end of the scale, assuming temperatures to rise significantly even in sparsely urbanized areas.

Other studies on village UHIs report findings connecting well to this study. Szegedi et al. (2013) showed for a similar-sized village in Hungary (9500 inhabitants) that UHII is lower (0.6°C) than that found in our study if the whole year is considered. However, maximum UHIIs of almost 2°C are reached on clear and calm days. Hinkel & Nelson (2007) confirm higher wind speeds to mitigate the UHI significantly in a village in Alaska (4500 inhabitants), but they also report a consistent urban–rural difference of 2°C during winter. While they emphasize the importance of anthropogenic heat release as the reason for pronounced winter UHII, the effect is much stronger than in Haparanda (0.3°C in winter), although the Swedish village is close to the Arctic Circle as well. This stronger UHII is likely because the building pattern is very dense, heating is more intense, and the difference between ambient air temperature and the heated structures is more distinct at the Alaskan site. Several villages (<10 000 inhabitants) at the southeastern Australian coast develop a substantial urban warming reaching 2 to 3.5°C on selected days in summer, when the effect tends to be strongest (Torok et al. 2001). Additionally, Steeneveld et al. (2011) showed for 2 villages in the Netherlands a mean maximum UHII of 1 to 2.3°C. Although a comparison might be difficult since various climate zones, village sizes, and building patterns are considered, we estimate our results to be similar to these studies nonetheless, particularly since single days exceeded 2°C in all 3 European villages examined here.

A stronger cold season UHII as observed in Cazorla is supported by other studies from the Mediterranean (Montávez et al. 2000, Papanastasiou & Kittas 2012). The smaller warm season difference is likely related to the fact that evaporative cooling at the rural site is particularly low when the vegetation suffers from drought stress and closes the stomata to mitigate water losses. This conclusion is supported by work revealing unirrigated lawns contributing less to regional cooling compared to their irrigated counterparts in Colorado (USA) urban areas (Bonan 2000). The rural sensor in Cazorla is mostly surrounded by olive plantations, and a study by Ben Ahmed et al. (2007) concluded that even irrigated olive trees in the Mediterranean basin reveal significant decreases in photosynthetic activity and hence transpiration. This would also support the increase in UHII during autumn and spring, when conditions are less stressful for the vegetation in terms of temperature and humidity. Several studies addressing similar latitudes as the Mediterranean region in East Asia confirm the existence of stronger nighttime UHIIs in winter (e.g. Kim & Baik 2002, Shen 2015). However, maximum UHIIs have also often been observed during daytime in summer (Zhang et al. 2005, Chan 2011), contradicting the finding from the Mediterranean that stressed vegetation contributes to lower urban–rural differences. Since the areas in East Asia discussed in this paragraph are highly urbanized, Zhang et al. (2005) explain the substantial warming during daytime in summer with an increase in anthropogenic heat sources like air conditioning, while Shen (2015) refers to severe air pollution coupled with low wind speeds as the main reason for a strong nighttime UHI in winter. Hua et al. (2008) find a regional pattern in UHIIs over China, with more severe urban warming in TN during winter in the north than in the south. Since the regional climate in the Mediterranean and East Asia is very different, this might as well be the reason for varying spatio-temporal intensities in UHI.

Proximity to open water could affect wind patterns and air temperatures, hence altering the UHII (Zhou et al. 2016). The small river Cerezuelo proved to be of great influence in Mediterranean Cazorla, reaching >4°C cooling in summer TN compared to the centre, but this phenomenon is substantially less important in temperate Geisenheim and boreal Haparanda. Hathway & Sharples (2012) showed the cooling by rivers to be dependent on relative humidity and ambient air as well as river temperature, with more effective cooling recorded if the river is cold and the ambient air warm. Not only are air temperatures considerably higher in summer in Cazorla (mean = 26.4°C) than in Haparanda (mean = 15.3°C) and Geisenheim (mean = 18.7°C), but the arid conditions contribute to lower relative humidity as well. In addition, the water originates from a nearby spring in the Cazorla mountain range and hence is very cold, whereas the 2 other villages are located hundreds of kilometres downstream, with water passing by that was already heated. As a result, a significant contribution to cooling in the Spanish Cazorla originates from the cold river Cerezuelo, a phenomenon that is substantially reduced in German Geisenheim and Swedish Haparanda, as is consistent with the study by Hathway & Sharples (2012).

4.3. Land cover effects

Some of the patterns found in European villages could be explained by circumstances already mentioned in Sections 4.1. and 4.2. This includes a weaker correlation between land cover and temperatures in Cazorla in general, likely caused by the complex terrain. Even though differences in elevation have been kept within a certain range, recent work indicated that topographic structures might have a significant influence on TN (e.g. Lindén et al. 2015a). Besides, during the warm season, the limited transpiration cooling from vegetation suffering from stomatal closure in Cazorla likely causes a reduction in the discrepancy between urban and rural sites. Significant interdependencies between temperature and vegetation are only detectable close to the sensors, decreasing rapidly with distance and defining the influential source area in Cazorla to <100 m. During the colder seasons, windy conditions and thick cloud cover in such mountainous regions might lower differences as well. Further work including the addition of more sensors in key locations and the analysis of wind conditions in different sites would be needed to address these issues and clarify the underlying reasons.

In Haparanda, vegetation contributes most substantially to cooling, with the effect being most pronounced in an area of 500 and 1000 m surrounding the sensors. The strongest effect occurs in summer, when vegetation is most productive and in this case not limited by soil water capacity due to the humid climate, although it is even detectable in the colder seasons with a cooling of −0.2°C per 10% vegetation coverage in spring, for example. If the vegetated area is considered for correlation in Geisenheim, a cooling could be confirmed that is most distinct in summer because transpiration is highest during that time. The cooling rate is presumably overall low in Geisenheim (−0.1°C per 10% vegetation coverage), because vineyards are characterized by lower photosynthetic rates compared to trees and forests as a whole. Model simulations (Dimoudi & Nikolopoulou 2003) as well as satellite-based investigations (Buyantuyev & Wu 2010) confirmed vegetation to lower temperatures significantly in urban areas.

In Haparanda as well as Geisenheim, exclusively significant coefficients are recorded if buildings were correlated with temperatures. The regression analysis confirmed a substantial warming caused by the built-up area as reported in other studies (Zhou et al. 2011, Coseo & Larsen 2014). In Haparanda, the coefficients of determination are highest in 500 and 1000 m radii, whereas in Geisenheim they decrease in these distances. Several other studies found a radius up to 500 m to be most relevant for spatial differences in urban temperatures (Hart & Sailor 2009, Yokobori & Ohta 2009). The 0.7°C warming per 10% building coverage calculated in Haparanda during spring is high if compared to Geisenheim (0.2°C per 10% building coverage). Because daytime in Sweden, and hence solar radiation, is massively prolonged in the warm season, a stronger impact caused by enhanced heating through urban geometry and materials is expected in late spring and early summer. This is likely coupled with a substantial anthropogenic heat release as is common for urban areas (Pigeon et al. 2007), more specifically being enhanced during wintertime as a consequence of mainly domestic heating, which stops in Geisenheim during spring. This might even lead to a greater UHII during the cold season compared to the season mainly influenced by radiation, as observed in Alaska (USA) (Hinkel 2007) and Hungary (Szegedi et al. 2013). Apart from that, Cazorla reveals less significant correlations and warming is solely notable in a radius of up to 50 m, which confirms temperatures to be more decoupled from land cover in this region.

As stated in Section 3.2., water bodies proved to have limited effect on cooling except for the river Cerezuelo. However, since this effect diminishes with increasing distance to a water body (Oswald et al. 2012), it appeared reasonable that significant correlations are constrained to a radius of up to 100 m considering the small size of the river. Steeneveld et al. (2011) found no significant correlation and showed that water bodies did not mitigate the UHI in several cities and towns in the Netherlands. A later study by Steeneveld et al. (2014) revealed that water bodies might also increase the maximum UHI because of the high heat capacity of water, lowering maximum temperatures during the day but contributing to warmer temperatures at night. While Geisenheim and Haparanda are in line with these findings from Central Europe, the Mediterranean Cazorla is an example for the mitigating effect water bodies might have for ambient temperatures, as described in other studies (e.g. Murakawa et al. 1991, Sun & Chen 2012).

Our analysis revealed correlation patterns to be predominantly decoupled from seasons. Even though absolute seasonal R^2 values between temperatures and land cover types vary, the seasons largely agree whether correlations are significant and which radii contribute most to a cooling or warming of local temperatures. With the reliability of the results from Cazorla being questionable because of the complex terrain, further work needs to be carried out to address the site-specific climatology and avoid additional heating by sunlight and to compare the results to another Mediterranean site with less complex terrain.

4.4. Implications of village UHI

The UHI and its intensity heavily depend on the rural reference. If the rural reference is already affected by anthropogenic influence, the UHII could perhaps be even larger than recorded. In earlier studies, stations located in settlements with several thousand inhabitants were considered rural and used to quantify the additional warming in larger cities (e.g. Gallo et al. 1993, Ezber et al. 2007). Since our study revealed a strong influence of small built-up areas in radii up to 1 km, many references likely underestimate the UHI in cities by overestimating temperatures measured in assumed rural locations. Consequently, airport stations used as reference (e.g. Street et al. 2013, Ketterer & Matzarakis 2014) might be biased too, as paved surfaces and buildings are nearby, although the pattern of built-up areas, paved surfaces, and vegetation is different from that in a city. A better approach of classifying rural stations in terms of a possible urban temperature bias is based on remote sensing, i.e. using night light data (Kalnay & Cai 2003).

We showed that the formation of a UHI is real in Haparanda and Geisenheim as well as in Cazorla, mainly caused by building density contributing to a substantial warming. This additional warming is very likely preserved as a bias in the records of all meteorological stations from these villages. Since the station in Cazorla is still positioned within the village and has not moved gradually from inside town to the surrounding rural area, as is the case in Haparanda and Geisenheim, even current measurements are affected and need to be used with caution.

5. CONCLUSIONS

A significant UHI was found in 3 European villages. The intensity is strongest in summer TN in temperate Geisenheim (1.1°C) and boreal Haparanda (1.4°C), whereas in Mediterranean Cazorla, other seasons show the greatest urban–rural temperature differences (~0.9°C). Limited plant activity due to warm and arid summer conditions likely limits cooling through transpiration in Cazorla, thereby leading to a less prominent discrepancy in summer compared to Central and Northern Europe, where summer temperature and moisture conditions are more favourable for plant growth.

Local TNs were found to be positively linked to surrounding building density in all 3 villages. In the boreal as well as in the temperate villages, the relationship is highly significant regardless of season and distance (ranging from 50 to 1000 m). In the Mediterranean climate, the relationship is strong close to the sensors but less so with increasing distance. Increasing building coverage by 10% resulted in a warming of spring TN by 0.3 and 0.2°C in Cazorla and Geisenheim, respectively. The warming is stronger in Haparanda (0.7°C per 10% increase in buildings during spring) and highest in summer, likely due to long-lasting solar radiation. Vegetation also contributed significantly to cooling in Haparanda (−0.2°C per 10% vegetation) and Geisenheim (−0.1°C per 10% vegetation). In Cazorla, the regression analysis indicated a significant cooling influence of vegetation solely in distances <100 m, except for summer, possibly due to the complexity of the terrain as well as the drought-stressed vegetation.

A distinct drop in summer TN by 4°C near the mountain river was detected in Cazorla, where temperatures are significantly affected in radii of 50 and 100 m. Similar effects are absent in Haparanda and Geisenheim, likely because ambient air temperatures are lower and water temperatures are higher. Although the strength and intensity of land cover influence on temperature seem to weaken with decreasing latitude from Haparanda to Geisenheim to Cazorla, all villages are affected by urban warming. This leads to a potential UHI bias in meteorological observations recorded in these locations and may affect the well-being of the inhabitants.

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