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Urban warming in villages

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Abstract. Long term meteorological records ($>$ 100 years) from stations associated with villages are generally classified as rural and assumed to have no urban influence. Using networks installed in two European villages, the local and microclimatic variations around two of these rural-village sites are examined. An annual average temperature difference (ΔT) of 0.6 and 0.4 K was observed between the built-up village area and the current meteorological station in Geisenheim (Germany) and Haparanda (Sweden), respectively. Considerably larger values were recorded for the minimum temperatures and during summer. The spatial variations in temperature within the villages are of the same order as recorded over the past 100+ years in these villages (0.06 to 0.17 K/10 years). This suggests that the potential biases in the long records of rural-villages also warrant careful consideration like those of the more commonly studied large urban areas effects.

1 Introduction

Changes in the surface energy balance of urban areas caused by, for example, increased thermal admittance of urban materials, limited radiative and advective cooling (due to urban morphology), lowered evapotranspiration cooling (due to sealed surfaces and reduced vegetation coverage), and additional anthropogenic heat release, tend to cause increased temperatures in urban areas compared to surrounding rural environments (e.g. Arnfield, 2003). This well documented urban heat island (UHI) effect is generally most pronounced in larger settlements with dense, tall built structures and sparse vegetation (e.g. Oke, 1982), but observable UHI effects are found in towns (e.g. Magee et al., 1999; Steeneveld et al., 2011) and small villages (Hinkel et al., 2003).

To assess long-term temperature trends, meteorological (met) stations are classified according to potential urban influence, e.g. “associated with urban area” or “rural”, where “rural” is considered to have no significant urban warming bias (e.g. Hansen et al., 2010). However, metadata from long-term “rural” stations often reveal that these stations are located in or near villages. The influences on met stations associated with large cities (e.g. populations $>$ 100 000) are well studied but the potential bias in small built-up urban areas, such as villages (e.g. populations $<$ 15 000, note this is not a precisely defined term), are not.

The objective of this study is to assess local and microclimatic variations around two long-term, rural-village, met stations, relative to their long-term records. The analysis uses air temperature sensors installed which are representative of the current and past met stations locations, as well as the general area.

2 Methods

A network of air temperature sensors was installed around a long-term Deutsche Wetterdienst (DWD) station in Geisenheim, Germany and a Swedish Meteorological and Hydrological Institute (SMHI) station, Haparanda in Sweden (Table 1). In the Global Historical Climatological Network (GHCN) database (http://www.ncdc.noaa.gov/ghcnm/) both are classed as rural. These villages currently have 11 000 and 5000 inhabitants, respectively (Hessische Statistische Landesamt, 2014; Statistiska Centralbyrån, 2014). Since the sites were initiated both villages have more than trebled their population (Table 1) and size of their built area increased, although the urban centres remains similar in structure and density. These two GHCN sites were selected based on their location, length of record, size of population, climate zone

Table 1. Description of examined met stations and associated village. Source of data are the meta-data archives of DWD (Deutscher Wetterdienst, Klima und Umwelt, Climate Data Centre, Frankfurter Straße 135, 63067 Offenbach, Germany) and SMHI (SMHI, Folkborgsvägen 17, 601 76 Norrköping, Sweden).

Station/ village name	Location	Altitude (m a.s.l.)	Climate	Station initiation year	Village pop. current/ initiation year	Description of built structure	Topography
Geisenheim	50.0° N 8.0° E	95	Temperate maritime	1882	11 000 3000	Dense village centre, mainly stone houses and impervious surfaces	hilly, up to 8° slope
Haparanda	65.8° N 24.1° E	4	Sub-Arctic	1859	4900 1000	Open structure, building material often wood, abundant vegetated surfaces	flat

Table 2. Description of temperature sensor network.

	Location	Site description/sensor placement (period station was there)	Elevation (m)
Geisenheim	Village centre (cen)	Open-set mid-rise built structure/on free standing post near central square	92
	River (riv)	Low plants, scattered trees, water/on post next to small road	83
	Residential (res)	Open set low-rise built structure/on street post	124
	Park (park)	Scattered trees/in park near the 1st location of the met station (1888–1915)	100
	Vineyard (Vin/met.stn.)	Scattered trees/on post in vineyard 155 m away from met station (1977–2006), and 180 m current met station (2006–ongoing)	116
Haparanda	Village centre (cen)	Open-set low-rise built structure/on post in vegetated yard surrounded by wooden 2-floor buildings, 40 m away from met station location (1859–1942)	5
	River (riv)	Low plants, scattered trees, water/on post, ∼ 150 m from met station location (1942–1977)	2
	Residential 1 (res1)	Open set low-rise built structure/on tree in garden, 3 m away from met station location (1980–2005)	10
	Residential 2 (res2)	Open set low-rise built structure/on post of met station (2005–2010) and 230 m away from station (1977–2005 – parallel stations)	6
	Met station (met.stn)	Scattered and dense trees/ on fence surrounding current met station (2010–ongoing)	9

and logistical possibilities following advice (personal communication from SMHI and DWD staff). The different characteristics (e.g. regional climates, built form, materials) are summarized in Table 1.

Temperature sensors (HOBO Pro v2 U23-001 in radiation shields RS1, Onset Computer Corporation, Bourne, MA 02532, USA) were installed at multiple sites in the village and vicinity (Table 2, Fig. 1) in mid-2013. Analysis of the meta-data files in the DWD and SMHI archives was used to identify past met-station locations so they, or comparable locations, could be instrumented. The sensors record a sample every 30 min. Analysis of the pre-deployment 22 day inter-instrument comparison, over a −4 to 18° C range, found the mean difference to be < 0.05 K, with < 5 % exceeding ±0.1 K (max 0.3 K). These inter-sensors differences are not removed so these values provide a measurement error. The data analyzed in this paper are for 321 and 352 days (data collection is on-going) in Geisenheim and Haparanda.

The Geisenheim station has been re-located multiple times, but due to incomplete metadata, the exact location is only known for the first and the last two locations. For the remaining three station locations, only minute-precision coordinates and short site descriptions are available. Sensors were deployed in the known sites, as well as in representative area types for the village and surroundings (Fig. 1). Although the current met station is situated to avoid urban influences (Behrendt et al., 2011) the nearby vineyard was used as a reference as unfortunately our sensor deployed at the current met site had to be removed for part of the year. The vineyard temperatures was found not to differ significantly based on analysis of concurrent data. In Haparanda the well documented previous met station locations were all identified for sensor placements (Fig. 1). The current met station is situated to avoid urban influence (Andersén, 2010) so can be used as a reference for analyzing the urban influence.

To examine potential urban effects, differences in measured maximum, average and minimum tem-

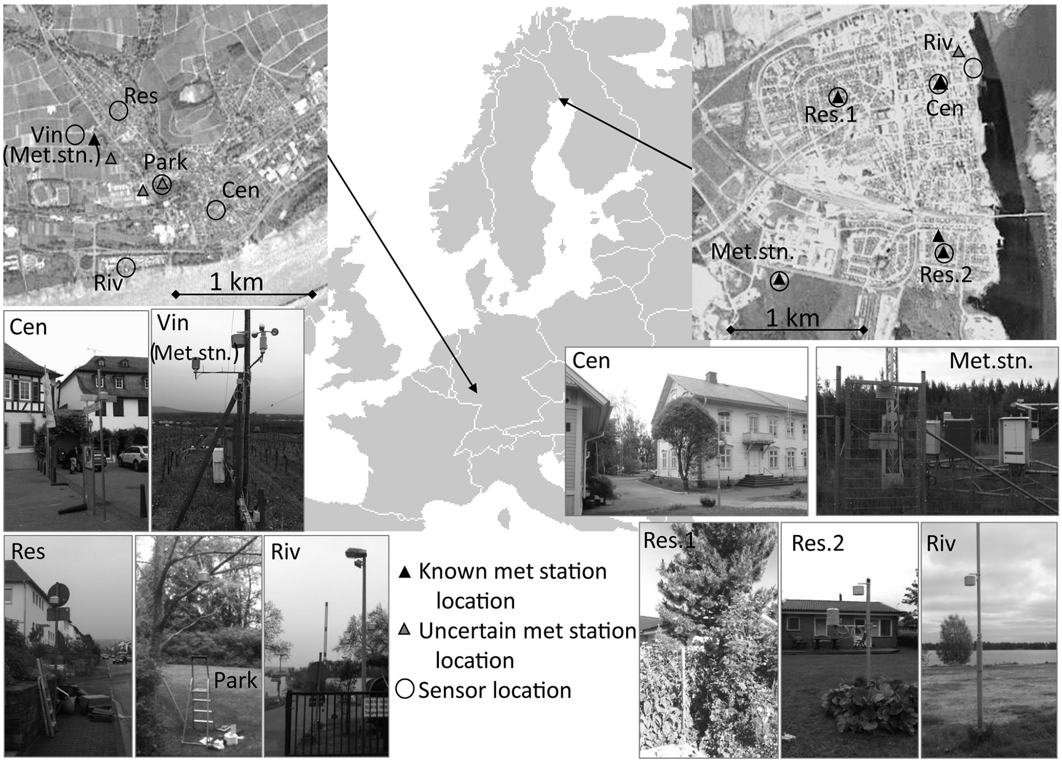

Figure 1. Location of the met stations and temperature sensors in Geisenheim (left panels) and Haparanda (right panels): previous (triangles) and current (black location known, grey location uncertain or has changed substantially since station was located there), circles mark sensor locations. Photos show locations of sensors used in this study. Satellite images from Google earth.

perature ($\Delta T_{max/avg/min}$), between the met station site and the remaining sites, were calculated for each day (e.g. $\Delta T_{max/avg/min(site)} = T_{max/avg/min\,(site)} - T_{max/avg/min\,(met.stn)}$). A t test was used to assess if the differences are significant. The DWD and SMHI station temperature data are used to calculate the long-term temperature trends. Elevation differences (up to 41 m) in Geisenheim will influence the temperatures, i.e. higher elevation sites are adiabatically cooler that lower sites (if all other characteristics are constant). However, since other factors influence each site causing differing effects whether max/avg/min temperature are considered (Blandford et al., 2008; Lindén et al., 2015), this was not accounted for in this study.

3 Results and discussion

3.1 Sensor network ΔT

The daily differences of the averages between each site and the met station site (ΔT_{avg}) by season (Fig. 2) are positive and mostly statistically significant, indicative of a warming influence in both villages. This finding supports the expectation that the current met station locations are cooler than previous sites, given they were located in the respective villages previously. However, this study did not establish whether the current met sites have any urban influence and if locations further away from the villages would have shown lower temperatures.

The warming influence is most pronounced in the two village centres, where significantly increased daily average temperatures were found in all seasons (median yearly $\Delta T_{avg(cen)} = 0.4/0.6$ K for Haparanda/Geisenheim). The surrounding residential areas have a smaller, but still significant, warming influence (median yearly $\Delta T_{avg(res)} = 0.1/0.2$ K) revealing patterns similar to those found in large urban structures: increased urban warming with increased building density and sealed surfaces. However, the overall magnitude of temperature residuals is smaller than that found in larger settlements (e.g. Svensson and Eliasson, 2002; Unger, 2004; Offerle et al., 2006).

Evidence of a moderating influence from waterbodies were found in both villages, particularly during summer, when higher minimum and lower maximum temperatures were measured near the rivers. In Haparanda, the influence in T_{min} was similar between the river and the village centre, though this could be an effect of the proximity of the river station site to the village centre, located upwind in general wind direction (Bergström, 2007). The slightly warmer temperatures found, especially in summer, in the urban park in Geisenheim could be a consequence of the proximity to the

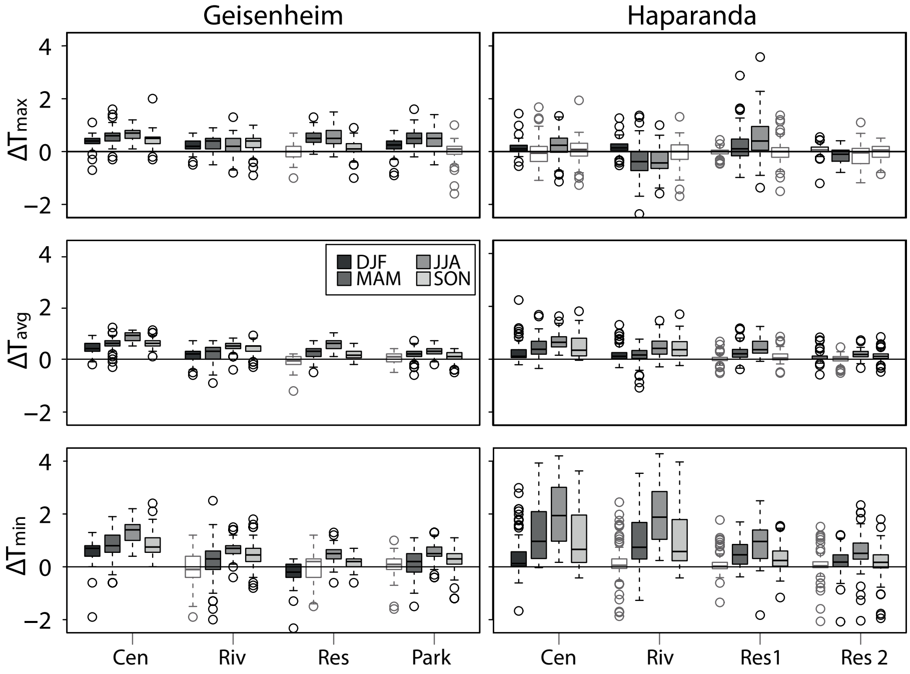

Figure 2. Boxplots of seasonal ΔT_{max} (top panels), ΔT_{avg} (middle panels) and ΔT_{min} (bottom panels), between the previous station locations/area typical environments and the current location of the met stations in Haparanda (left panels) and Geisenheim (right panels). Boxes show 25–75 percentile, with line across at median, whiskers extend to approximately 5–95 percentile and circles show outliers. Open, grey boxes are shown when sites do not differ significantly from the reference station or when difference is less than 0.1 K (due to accuracy limitations of the loggers). Site names see Table 2.

urban centre, as well as of prevented ventilation and nocturnal radiative cooling by the deciduous trees canopy (e.g. as shown by Spronken-Smith and Oke, 1998).

Temperature differences are larger for ΔT_{min} (median yearly $\Delta T_{\mathrm{min(cen)}} = 0.8/0.8$ K) and smaller for ΔT_{max} (median yearly $\Delta T_{\mathrm{max(cen)}} = 0.1/0.5$ K). This is a common result that is attributed the generally more stable nocturnal boundary layer preventing mixing of air from different areas, supporting site-specific nocturnal cooling (e.g. Krueger and Emmanuel, 2013). More unstable conditions caused by solar heating enhance vertical mixing which can generate horizontal winds that mitigate spatial air temperature differences. The timing of the maximum/minimum were generally consistent between sites in each village area on most days.

Substantial seasonal differences include more pronounced temperature residuals in summer than winter. The enhanced summertime solar radiation generates spatially heterogeneous heating of built and vegetated surfaces during the daytime. If strong surface heating occurs, the influence of site-specific nocturnal cooling is more important. The larger summer temperature differences (median $\Delta T_{\mathrm{min(cen)}} = 1.9/1.4$ K), are thus likely a result of the stronger solar influence compared to winter (median $\Delta T_{\mathrm{min(cen)}} = 0.1/0.6$ K). The seasonal pattern is especially pronounced in Haparanda. Given the high latitude (65.8° N) of that site, the mid-winter sun rises only around 3° above the horizon, while the sun does not set for a few weeks in summer.

Although the general patterns are the same in the two villages, several differences are found in the data. The larger ΔT in the Geisenheim centre is likely due to the taller buildings and denser urban centre with more sealed surfaces to house the greater population of Geisenheim. Furthermore, the variability in ΔT is smaller in Geisenheim. This may be a consequence of non-urban effects such as the differing relief causing cold air drainage, particularly during calm and clear weather situations, which prevents the development of strong spatial temperature differences (Bigg et al., 2014). If elevation was accounted for the warming bias in the village centre, park and river in Geisenheim would further increase, while that in the residential area would decrease.

3.2 Potential urban warming bias in data from the examined stations

Sources for inhomogeneity in climate data are many, for example, relocations of measurement sites, changes in surroundings, sheltering, exposure and instrumentation, calculation methods and observation practices (Aguilar et al., 2003). The urban influences documented in this study in Geisenheim and Haparanda are of the same order of magnitude as the temperature trends recorded in the long term records of the stations (Table 3). This suggests that station relocations in villages could potentially cause substantial bias in the data recorded and should be taken into consideration when homogenizing data.

Analysis of previous met station locations in the two examined villages (Fig. 1) show that at no point had the Geisenheim station been located in the village centre. Thus it is less likely to have been biased by urban effects. The station was originally placed in the centrally located park, which was slightly warmer than the current met station location. However, the north-west part of the park has been converted into a parking lot since the station was located there, which limits the possibility of accurately determining the exact bias for this location. Incomplete meta-data for some prior Geisenheim station sites only benefits from the knowledge they were always outside the most densely built area.

In Haparanda, the station was located in the village centre for the first 83 years of operation, then moved to the riverside (where several minor moves took place), then to two residential locations, before its current location outside the residential area. Historical maps show that the village centre is still very similar to 1924, which suggest the temperature differences from this study can be assumed to be close to those for the siting 90 years ago, although it is important to recognise that changes in heat sources (wood burning to central heating) and house insulation will have affected heat emissions by the local residents. Historically, the Haparanda station likely does contain an urban warming bias, primarily in data from the first station location (in the urban centre). The second location (river side) also shows a bias, likely a combination of warming from the nearby urban area and the river. The residential areas would have had a smaller but still significant bias, particularly in T_{min}. Given that the current met station appears to have less urban influences compared to all previous sites, correcting for such biases in the long record would result in an increased warming trend through the past 100+ years. Such a correction would, however, need to consider the population increase since the mid-19th century and other effects in building emissions and properties. As the general knowledge on how to avoid urban biases in station record has increased greatly in recent decades, it is likely that more rural-village stations have undergone transitions similar to the Haparanda station with the possibility that they include urban effects, likely stronger in earlier records. This should be considered when using such data for analysis of long-term climate trends.

4 Conclusions

In this paper it is shown that the urban effects in villages can be sufficient to significantly modify temperatures, thus potentially causing a warming bias in rural-village met stations. The effect is largest in minimum temperatures, and during summer, and influenced by latitude (stronger seasonal differences at higher latitude) and relief (less variability in the data in sloping terrain compared to flat). Urban influences of similar order were found in Geisenheim (Germany) and Haparanda (Sweden) potentially causing substantial biases in the temperature trends from these stations. Thus the classification of stations to indicate rural or village may provide a key flag to the interpretation of data in sets such at the GHCN.

Table 3. Linear temperature trend in the complete raw data set from DWD Geisenheim (1882–2014) and SMHI Haparanda (1859–2014), and median of the daily temperature difference between the village centre and the site of the current met station for the measurement period.

	Temperature trend, K $[10\,\mathrm{yr}]^{-1}$	Median $\Delta T_{(\mathrm{cen})}$, K
	Geisenheim	
T_{max}	0.06	0.5
T_{avg}	0.11	0.6
T_{min}	0.17	0.8
	Haparanda	
T_{max}	0.15	0.1
T_{avg}	0.10	0.4
T_{min}	0.17	0.7

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