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Removing the relocation bias from the 155-year Haparanda temperature record in Northern Europe

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ABSTRACT: The village Haparanda in northern Sweden hosts one of the longest meteorological station records in Europe depicting climate conditions in the subarctic. Since the station was relocated several times, moving gradually from urbanized to more rural areas, the record is likely biased by anthropogenic influences. We here assess these influences and demonstrate that even in villages urban heat island biases might affect the temperature readings. We detail a method to quantify this bias and remove it from the long Haparanda station record running since 1859. The correction is based on parallel temperature measurements at previous station locations in Haparanda. These measurements revealed a distinct urban warming pattern, largest in minimum temperatures during summer, since urban geometry and its heat capacity amplify additional warming and night-time heat release, especially during a period of high insolation and calm conditions. Due to the station movement from the village centre to the outskirts, the net correction results in an additional warming trend over the past 155 years. The trend increase is most substantial for minimum temperatures (+0.03 °C 10 years^{-1}). Maximum and mean temperatures are less affected (+0.01 °C 10 years^{-1}). An increase in trend is even more severe if the 20th century is regarded exclusively, displaying a rise in annual mean temperature trend by +0.03 °C 10 years^{-1} and +0.07 °C 10 years^{-1} in annual minimum temperatures, respectively. Our approach of using actual temperature differences between historical station locations did not take into account other factors that might have influenced the data such as changes in instruments or observers. The presented adjustment for temperature residuals caused by a change in historical station locations might be considered as a minimum approach to improve long-term temperature readings. The adjustment of the Haparanda station record results in an increased warming trend, thereby adding critical information to the evaluation and explanation of 20th century anthropogenic warming.

KEY WORDS urban climate; urban heat island; warming bias; homogenization; climate change; anthropogenic warming; relocation bias

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1. Introduction

The analysis of past and current climate variability and trends requires long-term, high quality instrumental meteorological datasets (Auer *et al.*, 2005). Instrumental data benefit from very high – monthly or even daily – resolution, but also covers a relatively short time period, as most coordinated measurements did not start before the 19th century (Brunet *et al.*, 2006). Although proxy data, such as tree-rings, ice cores or lake/ocean sediments, can be used to reconstruct climate variability of thousands of years back in time, high quality instrumental data are essential for calibration and verification (Esper *et al.*, 2007).

High quality meteorological data imply that the readings are homogeneous, and that variability and trends in the data are exclusively caused by weather and climate (Aguilar *et al.*, 2003; Venema *et al.*, 2012b). Even though efforts, such as sheltering and regular maintenance of instruments are made with the aim to produce homogeneous data, several biases have been identified within temperature series, particularly in long datasets (Tuomenvirta, 2001). The biases are caused by various events and procedures, like relocations, changes in observing practices or the introduction of new instruments (Böhm *et al.*, 2009). Station relocations have been shown to cause the majority of the detected inhomogeneities (e.g. Tuomenvirta, 2001; Brunet *et al.*, 2006; Syrakova and Stefanova, 2008; Böhm *et al.*, 2009; Rahimzadeh and Zavareh, 2014). A relocation or change in the environmental conditions of the station surroundings (e.g. construction of new buildings or removal of trees, etc.), may cause biases in the data due to alteration of the radiation balance and ventilation (Oke, 2006).

Prior to the introduction of automatic weather stations (AWS) some 15 years ago, meteorological observations required daily or sub-daily manual read outs. Due to the high labour intensity of this work, the stations were often positioned in connection to urban settlements to support accessibility. However, the data may thus contain an urban bias (Jones and Wigley, 2010). The urban bias is characterized as an intensified warming within urban areas which is

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typically most pronounced during night-time and in summer (Oke, 1982; Morris *et al.*, 2001), even though contrary results have been found as well, for example in Eastern Asia with a greater bias in winter (Yang *et al.*, 2013). This local warming phenomenon is called 'urban heat island' (UHI) and has been subject of many studies (Arnfield, 2003; Rizwan *et al.*, 2008). Various factors have been identified to affect UHI including an increased thermal admittance of construction materials, restricted radiative and advective cooling due to the urban geometry, and reduced cooling through evapotranspiration by sealed surfaces and limited vegetation coverage (Oke, 1982; Dimoudi and Nikolopoulou, 2003).

The urban warming bias generally intensifies with the size, population and density of an urban area (e.g. Oke, 1982). An additional anthropogenic heat release induced by traffic, domestic heating and industry can enhance the magnitude of UHI (e.g. Arnfield, 2003), but the influence of these factors might be limited outside of dense urban centres of major cities, such as New York and Paris (Allen *et al.*, 2011). On a global scale, the urban bias has proved to be small if not negligible (e.g. Parker, 2005, 2010; Trenberth *et al.*, 2007), but other work indicated locally substantial biases in, for example, the rapidly urbanizing China (Jones *et al.*, 2008; Ren *et al.*, 2008; He *et al.*, 2013) and the United States (Hansen *et al.*, 2001). Most UHI studies focus on greater cities throughout the world (e.g. Morris *et al.*, 2001; Huang *et al.*, 2008; Weng and Lu, 2008). Smaller urban settlements are less studied, even though UHI effects have been found in towns (e.g. Magee *et al.*, 1999; Fujibe, 2009; Steeneveld *et al.*, 2011) and villages (e.g Hinkel *et al.*, 2003; Lindén *et al.*, 2015b) as well. The scarcity of studies focusing on smaller urban settlements limits the possibility to assess the potential urban heat island intensity (UHII) affecting instrumental stations located in such environments.

In order to assess the homogeneity of long station records, access to detailed meta information including descriptions of historical changes in instrumentation and surroundings are crucial (Aguilar *et al.*, 2003). Metadata should contain coordinates, relocation dates, instrumental alterations, changes in observation practices and surroundings. The knowledge gained from these data, in combination with statistical homogenization procedures, offer the possibility to apply justified and detailed corrections of long station records (Brunet *et al.*, 2006). Most homogenization procedures using statistical tests for break point detection rely on the assumption that climate signals in nearby stations are similar, enabling the assessment of inhomogeneities by means of comparison (Venema *et al.*, 2012a). One such method is HOMER, a script developed within a European COST action (Venema *et al.*, 2012a) that has since been applied in numerous studies (e.g. Freitas *et al.*, 2013; Mestre *et al.*, 2013; Vertachnik *et al.*, 2015). However, long station records including data from the early 20th century or even the 19th century are rare, limiting relative homogenization approaches particularly during the early periods.

In this paper we present an empirical approach to estimate and remove relocation biases from one of the longest temperature datasets in the Nordic region, the 155-year record from the village of Haparanda, Sweden. The correction is based on parallel measurements to identify the spatial field air temperature variations within this village over a 2 year period.

2. Research site and methods

2.1. Study area

Haparanda is situated in the north of Sweden at the river Torneälv together with the Finnish town Tornio to the east and the Baltic Sea to the south (Figure 1). The climate is sub-arctic, with cold winters, cool and short summers, and no dry season (Köppen-Geiger classification: Dfc. Kottek *et al.*, 2006). The landscape is flat with altitude differences below 20 m a.s.l. within a distance of 5 km around Haparanda, and mainly covered by forest, wetlands and some agricultural fields.

Haparanda was first mentioned in the 17th century when it consisted of five homesteads. It gained town privileges with a population of approximately 550 in 1842, after having constructed a centre in the years before (Wasserman, 2009). The population grew to 2700 in the 1940, 4200 in 1970, and 4865 in 2010 (StatisticsSweden, 2015). However, historical maps (LandmaterietSweden, 2015) show that the original structure of the centre remained unchanged. The economic map of Sweden reveals that the centre in 1946 was essentially identical to today's structures with many buildings still being intact, while the urban area surrounding has slowly grown (Figure 1). Historical photos from around 1940 indicate that also the construction materials remained similar including wood as the dominating building material (Odencrants, 1945; Hederyd, 1993). Street paving was introduced gradually with most roads in the centre being surfaced in the 1940s. Horses were exclusively used until the 1920s when they were progressively replaced by cars. Also electricity was introduced in 1920s, but many houses are still heated by wood burning nowadays. Growth of the village has mainly been in the form of residential and commercial areas constructed some distance from the centre. Trade has been the main source of income in Haparanda, i.e. no major industries are located in the village.

2.2. Met station history

Meteorological measurements in Haparanda were initiated in 1859, making this one of the longest continuous temperature records in subarctic regions. However, metadata indicate several relocations within the village. For the first 83 years of operation, the station was located in a north-facing window cage on a wooden house in the village centre. It then moved to a free-standing screen in a nearby, less urbanized riverside location (where several minor moves took place), where measurements were performed from 1942 to 1976. Between 1977 and 2008, the station moved to three different residential locations,

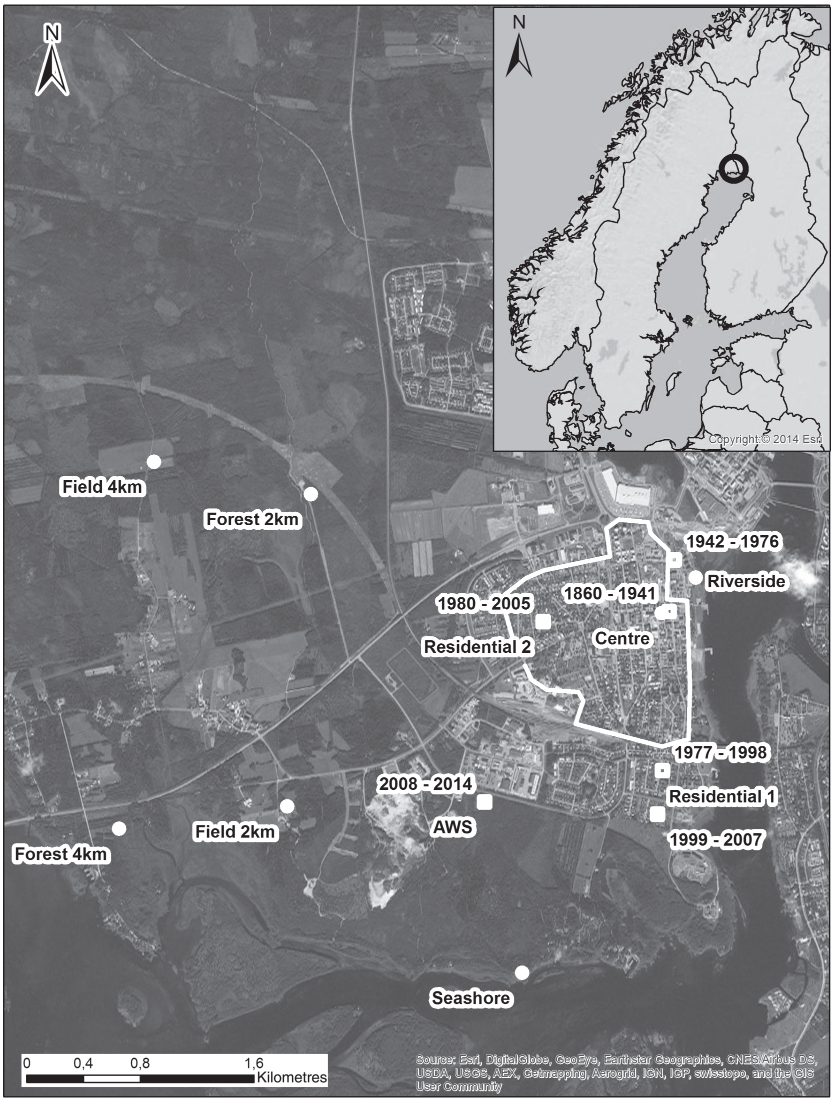

Figure 1. Meteorological station (white squares) and sensor locations (white dots) in Haparanda. Dates indicate periods of historical station positions including overlap periods among residential sites. AWS is the current station location. An outline of the urban area 1946 is displayed as well (white line). Maps from ESRI 2014.

before it arrived at its current location outside the residential area (Table 1, Figure 1). The station measurements in the residential areas were used in parallel as well as combined to form the Haparanda series during that time. Several changes in the observing staff took place but since this is poorly documented, it was not taken into account. Certainly, changes in instrumentation have taken place as well but no information on this is available either.

The complete temperature dataset as well as all metadata was provided by the Swedish Meteorological and Hydrological Institute (SMHI). The metadata consists of archived protocols written by the observers as well as reports written by people at the SMHI supervising the measurements and the observers. Mean monthly temperature data derived from daily averages showed no gaps since the beginning of the measurements, whereas minimum and maximum temperatures are missing between 1951 and 1960. Before 1914, the daily average was calculated using the Edlund formula ([T08 + T14 + 5*T21]/7) whereas from then on, the Ekholm-Modéns formula was used ([aT07 + bT13 + cT19 + dTx + eTn]/100; coefficients included are based on the respective month and geographical position of the met station – see Moberg and Bergström, 1997 for details). Since the installation of AWS, daily average is calculated as the arithmetic mean of all measured values. Even though several studies show that a change in calculation of mean temperatures might cause inhomogeneities (e.g. Tuomenvirta, 2001; Begert *et al.*, 2005), Moberg and Bergström (1997) reject that there is a considerable impact, at least in case of the Swedish temperature data they worked with.

2.3. Application of HOMER for bias identification

The homogeneity of the Haparanda record was tested using the HOMER package in 'R' (Mestre *et al.*, 2013). HOMER is based on the comparison of different climate stations, and the application of the program requires several data processing steps. The Haparanda dataset was used

Table 1. Previous station locations (top), current sensor sites for the assessment of the urban bias (middle) as well as sensors depicting the rural surroundings (bottom) in Haparanda.

Location	Site description	Alt (m)	Period
Met station			
Village centre	Instruments in cage outside a window of a north facing wall of a wooden house, small wooden buildings and some vegetation around, paved streets and walkways	4	1859–1941
Riverside	Station on lawn next to customs station, near town centre, next to the riverside	2	1942–1976
Residential area 1	Residential area, lawn, small houses with backyards	4	1977–1998 1999–2007
Residential area 2	*Parallel station! Residential area, lawn, small houses with backyards*	*10*	*1980–2005*
AWS	AWS station, outside city (about 200 m away from buildings), on grass/gravel next to forest	9	From 2008 on
U23 sensors			
Village centre	On lamp post on lawn, small wooden buildings and some vegetation around, paved streets and walkways	5	From 2013 on
Riverside	On lamp post on lawn, next to riverside, grass surrounding spot, greater buildings in some distance	2	From 2013 on
Residential area 1	On old met station post in garden with lawns and small wooden houses around	4	From 2013 on
Residential area 2	On tree in backyard with lawns and small wooden houses around	10	From 2013 on
AWS	On gate of AWS, outside city (about 200 m away from buildings), on grass/gravel next to forest	9	From 2013 on
Tidbit sensors			
Seashore	On tree 15 m away from sea, wet ground, forest/bushy area	1	From 2013 on
Field 2 km	On small tree in ditch with some more trees between fields with high grass, 1 km away from sea	8	From 2013 on
Field 4 km	On small tree in ditch with some more trees between fields with high grass, 4 km away from sea	10	From 2013 on
Forest 2 km	On tree in forest, widely spaced large trees, bushes and tall grass in openings, 3 km away from sea	10	From 2013 on
Forest 4 km	On tree in forest, widely spaced large trees, bushes and tall grass in openings, 0.5 km away from sea	4	From 2013 on

as candidate time series, and reference data were downloaded from the SMHI explorer (SMHI, 2015) and KNMI explorer (KNMI, 2014). The original data are provided by the Finnish, Swedish and Norwegian meteorological services. In order to acquire suitable reference station data, a search radius was applied with Haparanda as its centre. Due to a lack of sufficient data close to Haparanda, the radius needed gradual adaption. Finally, 22 stations within a range of 500 km distance to Haparanda were found which could be used for analysis, including four stations that reach back to before 1880 (Figure 2).

We used the HOMER break point detection to search for shifts within the time series. HOMER is capable of performing a pairwise detection as well as a joined detection when comparing the time series provided by the user. Breaks are detected based on statistical tests (like students *t*-test, maximum likelihood ratio) which check for a significant change in the data. This is coupled with an optimization scheme to assess the position most probable for the break, a moving window approach being one possibility for such a procedure (Venema *et al.*, 2012a). As a second step, we compared the findings with the relocation dates from the Haparanda metadata to check for compliance.

Unfortunately, the application of HOMER did not provide reliable indications of any relocation break points or environmental influence when performing both detection methods. Reasons for this are the great distances between Haparanda and the reference stations, the various climates included such as maritime and continental as well as the fact that there are too few records reaching back in time as long as they should in order to enable a good comparison. In addition to that, if there were break points of minor size, HOMER might not detect them since it is more moderate in terms of identifying inhomogeneities. This approach was therefore abandoned.

2.4. Temperature sensor network

In order to examine the potential relocation bias in the Haparanda temperature record, a network of temperature sensors (HOBO Pro v2 U23-001 in radiation shields RS1, Onset Computer Corporation, Bourne, MA 02532, USA) was installed considering the historical station locations (Table 1). Due to construction changes at the previous station locations, some adaptions had to be made. While the living house of the first station location (1859–1942) is still there, it was not possible to re-install a sensor at the window cage where the original measurements took

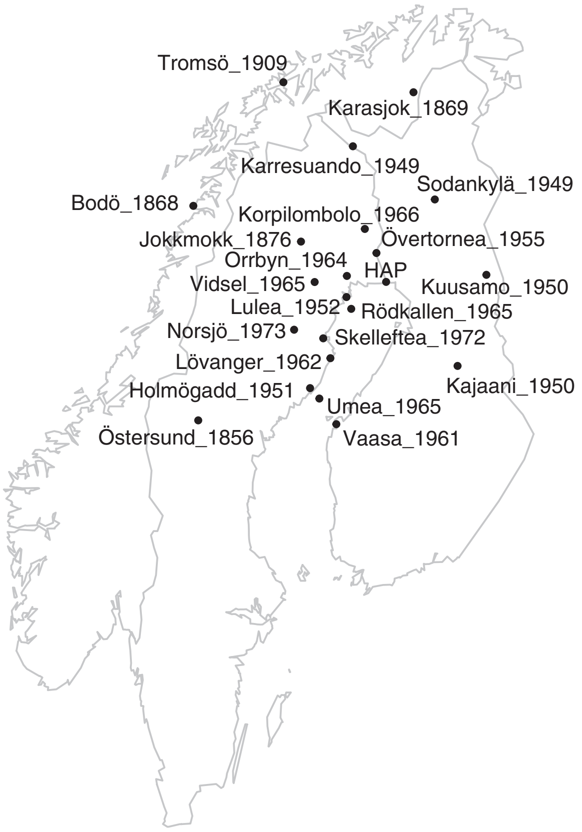

Figure 2. Haparanda and reference stations (black dots) used for the homogenization attempt with HOMER. The starting dates of operation are given as well.

place. Instead, a sensor was placed on a free-standing lamp post 40 m away from the original site. At the second location (1942–1977), several buildings were constructed since the met station was located here and the sensor was placed in a location ~100 m to the east, to resemble the description of the site according to meta-data. Since two of the three residential areas are practically identical to their appearance back in 1977, we simply placed the sensors close to the original station locations. The third residential site did change, however, but since this site closely resembled the first residential area, no additional sensor was deployed there and it will not be dealt with separately in the following.

All sensors were set to record a sample every 30 min. Analysis of a pre-deployment 22 day inter-instrument comparison, over a −4 to 18 °C range, found the mean difference based on 10 min data to be <0.05 °C, with <5% exceeding ±0.1 °C (maximum 10 min difference is 0.3 °C). These inter-sensor differences are neglected as they are rather small. Data from this sensor network was collected between 01 July 2013 and 30 June 2015 (data collection is on-going) generating a total of two complete years used in analysis in this paper.

In addition, smaller temperature sensors (HOBO Tidbit v2 Data Logger, Onset Computer Corporation, Bourne, MA 02532, USA) were placed in several locations around Haparanda in order to assess the rural temperature variability. These sensors measure with the same accuracy

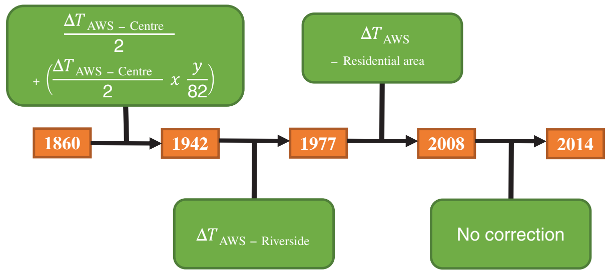

Figure 3. Correction of the relocation bias based on parallel sensor measurements in Haparanda. The long record starts in 1860 with the first year of complete data and was subsequently adjusted with regard to the following three major relocations.

and frequency as the U23 sensors. However, the Tidbit sensors were only protected from direct insolation by a white plastic cover which is directly applied to the sensor. In order to minimize radiation influences, only the night-time (minimum) temperatures were taken into account in this analysis. In total, five such sensors were installed in the outlying rural areas of different openness (forest/field), two in the north-west of Haparanda in 2 and 4 km distance to the village, and three in the south-west towards the Baltic Sea to capture potential maritime influences in 1 and 3 km distance as well as one at the shoreline (Figure 1, Table 1).

2.5. Data analysis

The half-hourly sensor data were averaged to daily mean temperature (TM), and the lowest and highest of the 48 measurements each day were used to define the daily minimum (TN) and maximum (TX) temperatures, respectively. Actual maximum and minimum temperature may occur between the half hour measuring intervals, resulting in a small negative bias for TX and a small positive one for TN. Due to logger storage limitations, it was not possible to achieve a higher temporal resolution and avoid this problem. TM, TN and TX were then used to calculate seasonal and annual averages. The monthly values were subsequently used to assess and correct the long station record, which is only available at monthly resolution. Besides, these allow a good graphical presentation of differences throughout the year.

As the current AWS is situated outside the village to avoid urban influence (Andersén, 2010), the corresponding sensor (U23) was chosen as a reference. To evaluate the AWS U23 as a rural reference, its monthly data were compared with the Tidbit sensors surrounding the village. This was done by calculating the residuals from the mean of all rural sites considering night-time (minimum) temperatures to avoid radiation biases:

$$\Delta T_{\min(\text{site})} = T_{\min(\text{Tidbit site or U23 AWS})} - T_{\min\_\text{average(all sensors)}} \tag{1}$$

As a second step, the difference between each former met station site and the AWS location was calculated:

$$\Delta T_{\max/\text{avg}/\min(\text{site})} = T_{\max/\text{avg}/\min(\text{site})} - T_{\max/\text{avg}/\min(\text{AWS})} \tag{2}$$

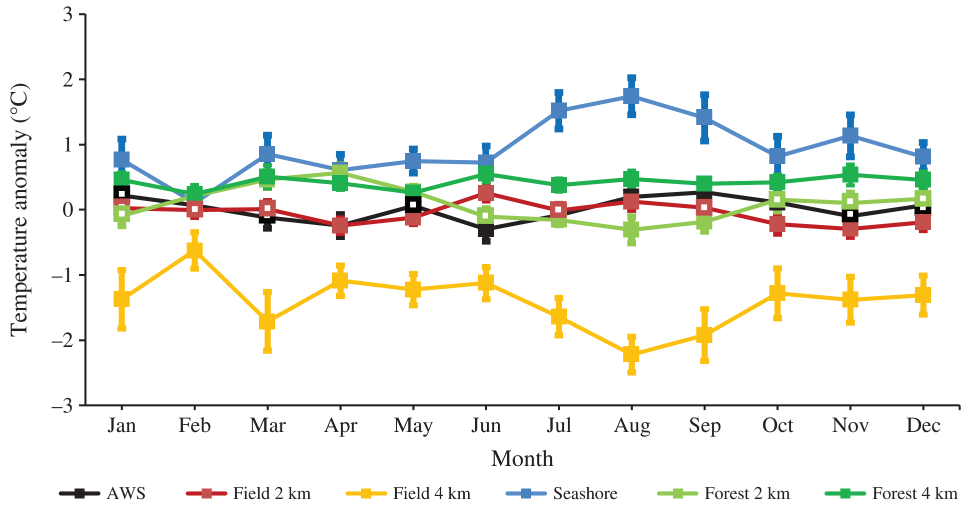

Figure 4. Seasonal pattern of temperature deviations recorded at Haparanda sensors over 2 years. Monthly temperatures are shown as anomalies from the mean of all sensors. Error bars display the variance as 95% confidence intervals. Filled squares mark significant deviations.

A pairwise *t*-test was performed to evaluate whether sensor differences are significant. The method was chosen according to a similar comparison of parallel measurements (Gallo, 2005). Monthly and seasonal confidence intervals (CI) were calculated for every sensor considering 95% confidence levels (CL).

2.6. Correction for relocation bias

The differences among the monitored historical met station sites were used to correct for the relocation bias in the long station record (Figure 3). The current location (AWS, 2008–2014) is considered free of urban influences and no correction was applied. The previous Residential 1 + 2 (1977–2008) and River sites (1942–1977) were corrected considering the temperature residuals between the representative sensors and the AWS site in order to account for the UHII. However, this simple way of generating a correction factor was not applicable to the initial station location. Considering the history of Haparanda, the village centre was already constructed at the time of station installation in 1859, but the urban area around the site grew substantially during the following 82 years of operation at this site. To account for this urban growth, half of the calculated difference between the centre sensor and the AWS sensor was regarded to be existent from the beginning on, the other half gradually added in the following years, with the intent of representing the increase in urban influence. This is a rather crude method of accounting for the urban bias in the early part of the long Haparanda record, but the lack of metadata information and parallel measurements prevent validation of other, more sophisticated, approaches. Furthermore, the initial Haparanda station was installed in a window cage, making an additional temperature bias, for example due to anthropogenic heat release, likely. Due to a lack of metadata, this bias is not addressed in this study, but this type of issues are common in early observational records and should be considered when relying on long term data.

3. Results

3.1. Haparanda temperature differences

In order to assess the rural temperature patterns and to evaluate the U23 sensor installed at the AWS as a rural reference, monthly TN of the AWS and Tidbit sensors are plotted as anomalies from the average of all sensors (Figure 4). The most striking deviations are the high sea shore temperatures, and the low inland field temperatures in about 4 km distance to the village. The seashore site was particularly warm in July (1.5 ± 0.3 °C) and August (1.7 ± 0.3 °C) whereas in winter the differences are much smaller. The 4 km field site is on average 1.4 ± 0.3 °C colder than the mean of all sensors reaching a maximum in August of 2.2 ± 0.3 °C. However, the 4 km forest site, located just 500 m from the seashore, is instead consistently warmer (annual average 0.4 ± 0.1 °C), even though the differences from the mean of all data are not always significant. The 2 km field and 2 km forest sites show smaller residuals (all months ≤ 0.5 °C), though they display inverse patterns, with the field being slightly warmer in summer and cooler during the other seasons. The AWS temperatures are similar to the mean of all sensors, with only 3 months deviating significantly.

In order to examine potential differences associated with the relocations of the Haparanda met station, the TX, TM and TN residuals relative to the modern AWS site were analysed (Figure 5). The differences vary both seasonally and diurnally and are most pronounced in summer and during night (TN). In TM and TN, every former station location displays positive monthly deviations, revealing the UHII. The village centre is characterized by maximum deviations reaching 2.2 ± 0.5 and 0.8 ± 0.1 °C in July TN and TM, respectively. The riverside sensor shows TN to be similar to the centre during warm season but different values in the cold season. In comparison to AWS, the residential area is ~0.4 ± 0.2 °C warmer throughout the year. In general, TN and TM patterns are relatively

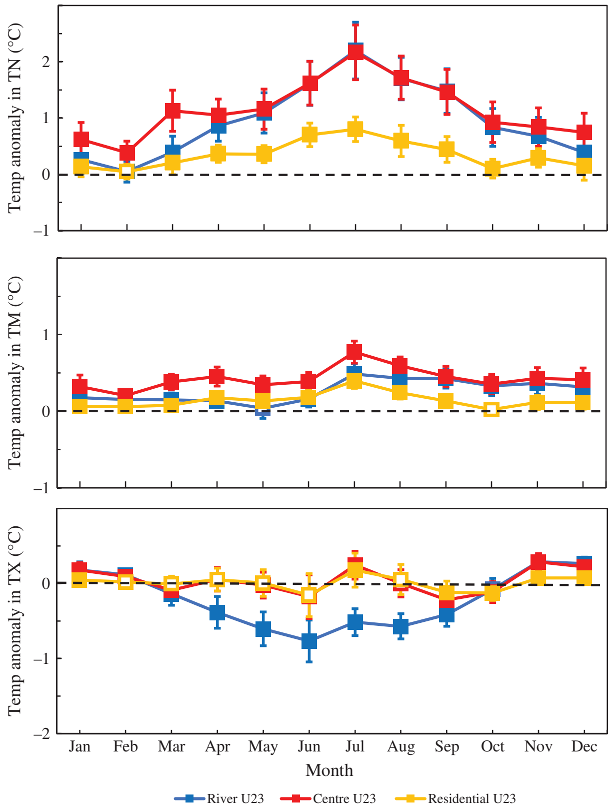

Figure 5. Temperature residuals between the historical thermometer locations and the current AWS station location. Monthly TX, TM and TN deviations including 95% error bars calculated over 2 years are shown. The residential values are an average of two sensors. Significant deviations are displayed as filled squares.

similar considering all sensors, with TM displaying less pronounced differences.

A comparison of maximum temperatures at the centre and river sites reveals a larger difference in summer compared to winter, obviously showing a distinct seasonal dependence. The riverside is more than half a degree cooler than the AWS site in summer, but deviates by just 0.1–0.2 ± 0.2 °C from December to February. The centre shows temperatures similar to the AWS site, with the largest deviation equal to 0.3 ± 0.1 °C in November, and no other monthly value exceeding 0.2 °C. Regarding the residential areas, the pattern is similar with temperatures deviating no more than 0.2 ± 0.2 °C in any month when compared to the AWS. Overall, the deviations are largest in the minimum temperatures, less so in mean and maximum temperatures, with the AWS being constantly cooler than all sites regarded with the exception of the warm season in TX.

3.2. Adjustment of the long Haparanda station record

The relocation bias in the long temperature series is removed for each month using the temperature residuals from sensor network (as detailed in Figure 3). A seasonal overview is presented in the following (Figure 6), considering monthly mean, minimum and maximum temperatures. Furthermore, an exemplary course of the residual applied to the time series is displayed later (Figure 7).

The correction generally lowered the temperatures, implying that the measured values were too high before (Figure 6). As the UHII is most pronounced in the village centre (station location 1859–1942), slightly lower at the riverside (1942–1978), and lowest in the residential area (1978–2008), the difference between raw and adjusted values decreases gradually towards present. The UHII was strongest during summer and in TN, and smallest during winter and in maximum temperatures. One exception to this pattern was found at the riverside location in spring and summer TX, revealing a slightly positive correction and hence the corrected time series to appear above the original one during that time. As the bias is larger in the earlier part of the record, the warming trend of the corrected data increased compared to the uncorrected (Table 2). This was most pronounced in TN where the annual trend rose from 0.18 to 0.21 °C 10 years^{-1} over the whole period of 155 years. As consequence to the corrections made, the new trends show the largest increase in summer and the least in TX.

The trends for the period from 1901 to 2000 were analysed as well. The overall pattern proofs to be similar to the 155 year period already discussed, indeed displaying more severe differences regarding the trends. An annual trend increase by 0.07 and 0.09 °C 10 years^{-1} in summer could be observed for TN, respectively. Comparing the corrected and the original record revealed a substantial rise in trend of 0.03 °C 10 years^{-1} in annual mean temperatures, resulting from the strong correction in the early part of the record. Only maximum temperatures show no difference if the 20th century is considered instead of the whole 155 year record.

4. Discussion

4.1. Suitability of the rural reference

The comparison of the temperature sensors revealed a significant thermal variability in the village of Haparanda as well as in its rural surroundings, with most pronounced differences in summer nights (TN). As one of the objectives of this study was to identify UHI, identification and verification of a representative rural reference is crucial. Temperature variability within pre-defined rural areas can, however, be substantial, e.g. due to changing land cover as well as vegetation type, height and density (Grimmond *et al.*, 1993; Hawkins *et al.*, 2004; Lindén, 2011; Lindén *et al.*, 2015b). In addition, the increased heat capacity of water can have moderating effects on rural temperature variability (Oke, 1987). Since the landscape is flat without any abrupt changes in altitude, the topography is assumed to be insignificant in the analysis.

These influences also seem to be important in Haparanda, where the seashore location showed considerably higher TN than the other rural stations. The considerably lower TN in the open inland field compared to the forested sites indicated radiative cooling to be an important factor of rural temperature variability as well (Hawkins *et al.*, 2004). The site of the current AWS

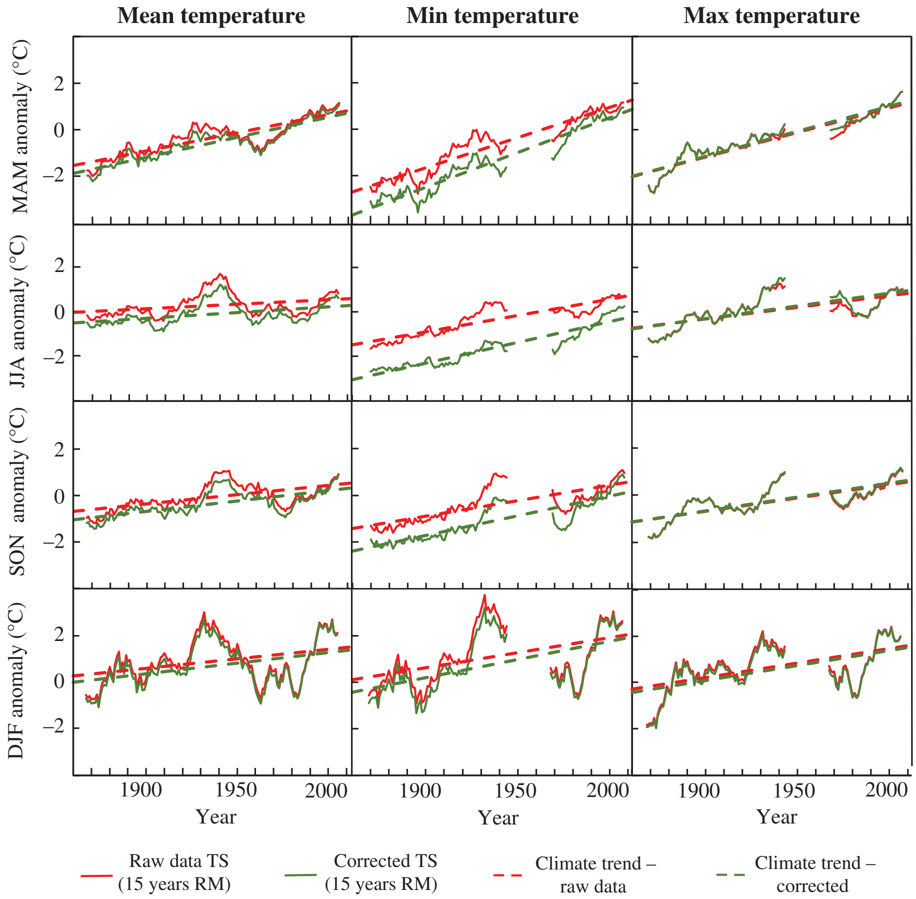

Figure 6. Raw and adjusted seasonal TM, TN and TX time series of the long Haparanda station. Curves are smoothed using a 15-year running mean, dashed lines display linear trends over the period 1860–2014. Temperatures are plotted as anomalies relative to the climate period from 1961 to 1990. The gap in TN and TX is due to missing data.

in Haparanda, surrounded by a young forest stand and installed according to standard protocol for AWS stations (Andersén, 2010), did not differ significantly from the rural mean TN. We interpreted this as proof of no indication of urban influences on the current AWS site. This conclusion is, however, limited as the rural variability of TM and TX could not be examined in the rural network since direct insolation effects on the Tidbit sensors bias the results. As the spatial differences in the urban sensor network is most pronounced in TN, it appears likely tough that the deviations from the rural mean are similar or lower in TM and TX, implying that the AWS sensor is area-representative as a rural reference.

4.2. Determining the urban bias

The analysis of a sensor network over 2 years revealed a significant long term bias in Haparanda due to differing UHII in relation to the AWS as a rural reference. This bias is not confined to a certain season but persistent throughout the year. As frequently reported in urban climate studies, the UHI was most pronounced in the urban centre, and decreased with building density (e.g. Stewart and Oke, 2012). In line with existing evidence (Klysik and Fortuniak, 1999; Morris *et al.*, 2001; Huang *et al.*, 2008), UHI is also most pronounced in minimum temperatures during summer. The long-term summer urban TN bias in Haparanda (1.8 °C) equals approximately half of the summer UHI reported from large cities under optimum conditions such as Lodz, Poland; 700 000 inhabitants (Klysik and Fortuniak, 1999) and Melbourne, Australia; 4 000 000 inhabitants (Morris *et al.*, 2001), and approximately one-third of the ΔTM found in the town of Hania, Greece; 100 000 inhabitants (Kolokotsa *et al.*, 2009), even though not being directly comparable due to different measurement procedures. This shows that the influence of the urban area on temperatures needs to be carefully considered also for smaller urban settlements.

The town of Tornio, population 22 000, is located on the Finnish side of the Torne river across from Haparanda, with a small commercial centre 500 m towards north east of the sensor placed by the river and could thus potentially influence temperatures. However, the population density of Tornio is very low, 18 inhabitants km^{-2} for the whole municipality and the actual population in the near vicinity of the measurements used in this study is very low as well. A study by Lindén *et al.* (2015a) found significant correlations between mainly non-urban temperatures and built/paved elements in the surroundings up to a distance of 1000 m, and source areas between 30 and 500 m have

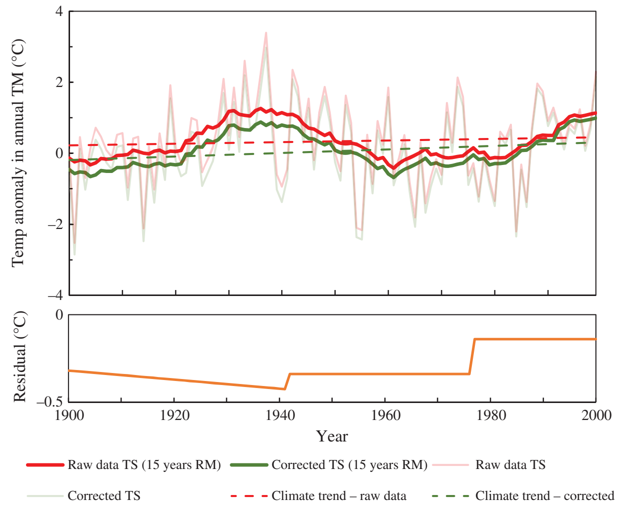

Figure 7. Raw and adjusted annual mean temperatures of the Haparanda station record with smoothed curves as a 15-year running mean. Dashed lines display linear trends over the period from 1901 until 2000. Temperatures are plotted as anomalies relative to the climate period from 1961 to 1990. The residual used for obtaining the corrected series is shown below.

Table 2. Trends in corrected and uncorrected seasonal and annual TX, TN, and TM time series. Temperature trends in °C 10 years^{-1} calculated over the period 1860–2014 are shown.

Parameter	Spring	Summer	Autumn	Winter	Year
	Uncorrected				
TX	0.23	0.11	0.14	0.15	0.16
TN	0.26	0.15	0.14	0.14	0.18
TM	0.17	0.04	0.10	0.11	0.11
	Corrected				
TX	0.23	0.13	0.14	0.16	0.17
TN	0.29	0.18	0.17	0.17	0.21
TM	0.19	0.06	0.11	0.12	0.12
	Difference				
TX COR – UNCOR	0.00	0.02	0.00	0.01	0.01
TN COR – UNCOR	0.03	0.03	0.03	0.03	0.03
TM COR – UNCOR	0.02	0.02	0.01	0.01	0.01

been found to be most representative in studies of the urban climate (Hart and Sailor, 2009; Li and Roth, 2009; Yokobori and Ohta, 2009; Lindén, 2011). Tornio has a low population density and in combination with its location >500 m downwind it is assumed to not have a significant influence on the climate of Haparanda.

In sub-arctic Haparanda, strong summertime solar radiation generates spatially heterogeneous heating of paved and vegetated surfaces during daytime. This is emphasized by a non-existing sunset for most of June. Even in July and May, the duration of a day is never below 17 h. The differing radiation absorption along with the heat capacity are the basis of the severe site-specific differences in nocturnal cooling. As the mid-winter sun rises only about 3° over the horizon in Haparanda and daylight is limited to less than 5 h, impact of direct and diffuse solar radiation is minimal during the cold season. The smaller, but still significant, bias found in winter (TX = 0.2, TM = 0.3, TN = 0.6 °C) likely results from anthropogenic heat release, as is also reported both in the small village of Barrow (population: 4200), Alaska (Hinkel and Nelson, 2007) but also in the large city of Seoul (population: 10 000 000), Korea (Kim and Baik, 2005).

The sensor placed at the Haparanda riverside is located downwind from the village centre considering the prevailing wind direction (Bergström, 2007). The TN bias found at this site is thus likely a combination of warming from the central urban area as well as a result of the water energy balance particularly during summer and autumn. The lower winter and spring TM/TN bias at the riverside is likely due to the fact that the river is frozen from late autumn until May (Persson, 2012). The cold bias in summer TX is likely due to the greater thermal capacity of the water, moderating daytime warming (Hathway and Sharples, 2012). The slightly cooler TN in winter is explained by the sensor's location further away from buildings (~35 m) and reduced wind protection supporting air mass exchange and cooling (Bonan, 2000; Benzerzour *et al.*, 2011). In the residential area, the mix of rural and urban elements generates a lower, but still significant urban bias, as also found in Toulouse (population: 450 000), France (Houet and Pigeon, 2011, http://www.ncbi.nlm.nih.gov/pubmed/21269746/), for example.

Since the sea proved to be an important factor for local temperature pattern, the sites within Haparanda and the AWS site outside the village might be influenced differently according to their distance to the seashore, even though they are several kilometres away. Therefore, a difference in temperature between these locations might not exclusively be caused by the degree of urbanization in their vicinity. With increasing proximity to the sea, a compensatory impact for urban warming is likely to occur, though the extent might be limited due to the existing distance. Nevertheless, the correction succeeds in eliminating the relocation bias no matter the source.

4.3. Adjusting the long Haparanda temperature record

The results from the sensor network demonstrated a significant urban warming in a small urban settlement. The categorization of village met stations as 'rural' in global databases (e.g. NOAA, 2014), implying that data from those locations are free from urban biases, needs to be reconsidered, at least for Northern Europe. Our sensor measurements indicate that the repeated relocations of the Haparanda station have gradually reduced the bias caused by different UHII, and a removal of relocation bias, even though strengthening the warming trend, is thus needed to improve data reliability.

The identification and adjustment of relocation bias is not feasible using classical homogenization tools, such as HOMER, due to the lack of suitable long reference station records in its vicinity. The application of HOMER to the Haparanda station record revealed no break points that are in line with meta-information. The only way to handle relocation biases in such an environment seems to be a monitoring of spatial temperature patterns by running a detailed network of temperatures sensors as done in this study.

This basic correction approach based on parallel measurements mounted at the old met station locations has some weaknesses. The correction procedure applied here is based on the assumption that the sensor measurements are representative for the UHII throughout station history. Historical maps and photos were used to evaluate the building structure and land cover, indicating very similar and partly identical structures since the first relocation in 1942. Analysis of this meta-information also demonstrated that urban growth has taken place at the outskirts of the village, indicating that our sensor measurements are representative for this period. Population growth may have generated an increased anthropogenic activity including traffic. However, Haparanda has long been a centre for trade, with high activity in the village centre throughout the 20th century, and traffic has in previous studies proven to have very limited influence offside the main roads (Pigeon *et al.*, 2007), and is therefore unlikely an important heat source in the small centre of Haparanda. Historical photographs and maps also show that during the initial 82 years of the Haparanda record the village centre structure was already similar to today, though this period is likely to have seen considerable changes in street paving and the heating of buildings. The gradual increase in impermeable ground (e.g. paving of streets) up until the 1940s would likely affect the urban energy balance to some extent. However, since the sensor was placed on a lamp post above a meadow and the old station was installed outside a house above a meadow as well, the direct influence of the surrounding ground cover is not causing a bias. During the course of the Haparanda station changes, alterations in the anthropogenic heat sources are also likely to have occurred. Information that would enable correction for this potential anthropogenic bias is unfortunately not available but it can be argued that for example an increased domestic heating today is likely compensated by improved isolation in modern buildings. Furthermore, the influence of anthropogenic sources on temperatures has been found very limited outside of dense urban centres, especially when all weather conditions are regarded (Allen *et al.*, 2011). Since historic sources (Section 2.1) indicate that building structure and human activity in the village centre was relatively similar at the initiation of the Haparanda station an influence on urban temperatures likely existed in the village centre from the start. However, due to the growth in surroundings as well as changes in surroundings and activity, the bias at station initiation was not likely of the same magnitude. In order to avoid an over-estimation of the bias, it was therefore assumed to equal only 50% of the current urban bias at the station's initiation in 1860, and gradually increasing to reach 100% at the time of relocation in 1942. This simplistic approach reduces the risk of overestimating the early bias. It is possible, however, that the window cage placement in the original location caused some additional warm bias due to building heat leakage and insolation effects, particularly during summer, but such biases can only be handled usefully by parallel measurements (Böhm *et al.*, 2009). For instance, Nordli *et al.* (1997) found no effect on winter TM in their Nordic dataset for instruments having been moved from a window cage to a free-standing screen, but a rise in summer TM of 0.0–0.3 °C.

In Haparanda, the relocation bias is consistently negative, and homogenization led to an increased temperature trend in minimum temperatures by up to 0.3 °C 10 years^{-1} over the whole met station measurement period. A consistently negative relocation bias was also found in an North Atlantic climatological dataset (Tuomenvirta, 2001), and an increased temperature trend after homogenization has been reported in Switzerland (Begert *et al.*, 2005), Spain (Brunet *et al.*, 2006), China (Yan *et al.*, 2010; Yang *et al.*, 2013) and Iran (Rahimzadeh and Zavareh, 2014), for example. Since meteorological stations generally moved from centres to the outskirts or out of the urban area, the gradual warming caused by steady urbanization which enhances the warming trend is reduced. Relocation procedures are usually accomplished to reduce the urban influence and as a result, the original time series contains less urban warming towards present. By correcting for the relocation bias, the UHII bias is recovered in the adjusted dataset, thus resulting in an increased warming trend (Zhang *et al.*, 2014). This study shows that also smaller urban settlements such as towns and villages need to be carefully evaluated to avoid an UHII bias in long term temperature trends.

5. Conclusions

Based on 2 years of parallel measurements at ten locations, a substantial UHI was found in the village of Haparanda in northern Sweden. The UHII increases towards the village centre and is strongest in minimum temperatures during summer. The analysis of historical locations of the Haparanda meteorological station shows that the long temperature record from this village contains a bias caused by station relocations from the urban centre towards the outlying forest area, reaching 1.8 °C in summer minimum temperatures and 0.4 °C as an annual mean. We here used the temperature residuals between the different station locations to remove the relocation bias from the 155-year Haparanda record. Since the bias is stronger during earlier periods, data homogenization increased the warming trend in the temperature record by up to 0.03 °C 10 years^{-1} over the whole period. As efforts to reduce non-climatic influences on met stations records generally increased towards present, it is possible that similar trend-limiting biases are inherent to other relocated station records. This specific homogenization method is time consuming and requires detailed monitoring data, and is therefore not applicable to large scale datasets. However, the Haparanda example might indicate that relocation biases are also important in records from other smaller towns and villages, and shows how such biases can be adjusted without relying on nearby reference stations.

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