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Detection and elimination of UHI effects in long temperature records from villages – A case study from Tivissa, Spain

Manuel Dienst[a,*], Jenny Lindén[b], Òscar Saladié[c], Jan Esper[a]

[a] Department of Geography, Johannes Gutenberg University, Mainz, Germany
[b] IVL – Swedish Environmental Research Institute, Gothenburg, Sweden
[c] Department of Geography, Universitat Rovira i Virgili, Vila-seca, Spain

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ABSTRACT

Since villages are usually regarded as part of the rural area, associated temperature records are assumed to be free of urban influences and might be used as unbiased reference data for city records. However, based on two years of data from a high temporal and spatial resolution sensor network, this study proves the development of a substantial UHI in the Spanish village Tivissa with intensities of > 1.5 K in summer T_{min} and T_{max} compared to a rural reference. Hosting a meteorological station that has been relocated several times within Tivissa during its > 100-year history, we here detail a method to remove UHI biases at past measurement sites to create a more reliable rural temperature record. Adjusting the time series results in a trend increase of up to 0.1 K per decade in T_{min}, while T_{max} trends are slightly reduced. Comparing the adjustments based on station history with adjustments produced by employing a commonly used statistical homogenization method reveals substantial differences of > 3 K between these approaches. Applying the presented method to a greater number of stations is problematic though, as it is laborious and requires a suitable sensor network as well as detailed metadata.

1. Introduction

As far back as Roman times, people considered the climate in cities to be different and thought about ways to address that in town planning (Rykwert, 1988). Great progress has since been made to understand the complex processes determining the urban climate. A major aspect in this field of research is the establishment of an urban heat island (UHI), a rise in urban temperatures compared to the rural surroundings (Landsberg, 1981). The amplified warming is mainly caused by the introduction of new materials and a change in geometry as well as anthropogenic heat release as summarized by Rizwan et al. (2008). Although there are inter-urban variations, outgoing longwave radiation is usually lower in cities due to radiation trapping within narrow streets with high buildings (Unger, 2004). In addition, the introduction of new materials changes the heat capacities and might lower albedo values, which is an essential component of UHI formation (Giridharan et al., 2004). Naturally, urbanization causes the amount of vegetation and bare soil to decrease as they are replaced by sealed surfaces, lowering the latent heat flux originating from evapotranspiration (Oke, 1982). Furthermore, wind speed is usually lowered in urban canyons and hence ventilation is limited, which not only prevents the removal of pollutants in cities but also intensifies urban warming (Dimoudi and Nikolopoulou, 2003).

UHIs have been reported from cities all over the world (e.g. Emmanuel and Krüger, 2012; Gaffin et al., 2008; Kim and Baik, 2004; Saaroni et al., 2000). Many studies have also indicated that continued urbanization gradually increases the UHI (e.g. Brandsma et al.,

* Corresponding author at: Department of Geography, Johannes Gutenberg-University, Johann-Joachim-Becher-Weg 21, 55128 Mainz, Germany.
E-mail address: m.dienst@geo.uni-mainz.de (M. Dienst).

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2003; Ghazanfari et al., 2009; Hamdi et al., 2009; Zhou et al., 2004). This might have implications for meteorological measurements and especially for long temperature time series, since many stations were initially located in urban areas. Several studies demonstrated that the correction for the urban impact in long time series had a considerable effect on recent warming trends (e.g. Balling Jr and Idso, 1989; Kato, 1996; Wang and Ge, 2012). The development of UHIs has been confirmed also in small urban settlements like villages, though such studies are still rare (Dienst et al., 2018; Hinkel et al., 2003; Szegedi et al., 2013), emphasizing the need to expand research on small urban areas.

Nowadays, the siting of meteorological stations is carefully regulated in order to minimize the impact of site specific features such as nearby slopes, buildings or vegetation (WMO, 2011). This procedure aims at reducing non-climatic impacts as well as representing the regional rather than the site-specific climate. However, the records may be influenced by factors such as changes in observing staff, variations in observing times, changes in instrumentation, and station relocations (Böhm et al., 2009). The potential for anthropogenic biases is high in century-long temperature records, since the stations tend to be originally placed within the urban centres in order to provide high accessibility for manual read outs. Over time, the stations were often moved gradually to a more rural surrounding. Relocating a station has been proven to substantially affect long temperature records, as it often involves significant changes in station environment (e.g. Brunet et al., 2006a; Tuomenvirta, 2001). In order to produce high-quality long term temperature data, a homogenization is usually performed, aiming to remove these inadvertent alterations (Venema et al., 2012). One widely used homogenization method is the HOMER script, which executes a statistical analysis of a temperature time series and performs a comparison with neighbouring records, including an assessment of breakpoints and differences among the series and a subsequent adjustment to the overall regional climate signal indicated by the other records (Freitas et al., 2013; Mestre et al., 2013).

Meteorological data gathered in village locations is often regarded as rural. In widely used databases like the KNMI Climate Explorer (Trouet and Van Oldenborgh, 2013) or the GHCN (Hansen et al., 2001; Peterson and Vose, 1997), population data serves to classify whether a record is urban or rural. A rural station is considered to be free of anthropogenic influence and might be used as a reference to study urban influence in other temperature datasets. However, if villages develop substantial UHIs, as the previously mentioned studies suggest, a reconsideration and possible correction of the rural dataset is inevitable.

In this study, we aim to identify the UHI in the village Tivissa, Spain, and use this knowledge to remove UHI biases from a century long time series recorded in this village. The corrections are based on two years of temperature measurements recorded by a network of sensors placed at all historical sites of the meteorological station. We first assess the differences of these measurements to a rural reference, located outside the current village structure, in order to assess the varying UHI intensities in the station's historic locations. After correction, we evaluate the differences in warming trend for the original and the corrected dataset. In a former study, we used a similar approach to assess and remove the relocation bias in a long temperature record from a village in Sweden (Dienst et al., 2017), mainly because statistical homogenization failed due to a lack of suitable reference stations. As the Tivissa time series has previously been homogenized using the HOMER method, we here compare both correction approaches by means of residual calculation. Since HOMER aims at rectifying all non-climatic influences in a record, we aim to estimate whether the homogenization properly removes the presumed UHI bias in rural station data.

2. Study area and methods

Tivissa was chosen for this study because it fulfils several criteria, including a low number of inhabitants, a long temperature record (> 100 years), an unchanged townscape for that period, and a meteorological station subjected to several relocations within the urban area and thus likely exposed to a varying degree of UHI intensity. We here first detail the study site and history, followed by a description of the methods to detect and remove UHI effects in the long station record.

2.1. Study area

Tivissa is situated in the Autonomous Region of Catalonia in the North-eastern part of Spain, with the river Ebro running in 6 km distance to the West and the Mediterranean Sea in 12 km distance to the South-east (see Fig. 1). The village is located at the foot of the Serra de Llaberia and Muntanyes de Tivissa-Vendellòs at an altitude of 315 m a.s.l. The landscape is dominated by hilly and mountainous terrain, valleys being mostly used for agriculture and the mountain slopes covered by open forests. Based on the updated Köppen & Geiger climate classification by Kottek et al. (2006), the region is regarded as a warm temperate climate zone with dry and hot summers (Csa).

Despite having a history that dates back to Iberian and Roman times, the village is dominated by the medieval centre nowadays. White and brownish one- to three-storey houses exist alongside or integrated in the medieval structures, with narrow streets and alleys in-between. The expansion of the village was limited during the 20th century and mainly took place to the south-west of the centre in the 80s, introducing a new residential area. Only few houses have been built since the beginning of this century next to this expansion. In 1910, population size of the village was 2400 inhabitants, but declined afterwards, especially after the Spanish Civil War. Since the beginning of the 21st century, Tivissa is home to 1400 people, and still shrinking.

2.2. UHI detection

In order to correct the long temperature record from Tivissa for UHI effects, it is essential to reconstruct the history of past measurement practices and sites, and to assess the UHI intensity at these locations. With measurements starting in 1911 (precipitation) and 1912 (temperature), respectively, and still ongoing, the meteorological station in Tivissa provides one of the longest

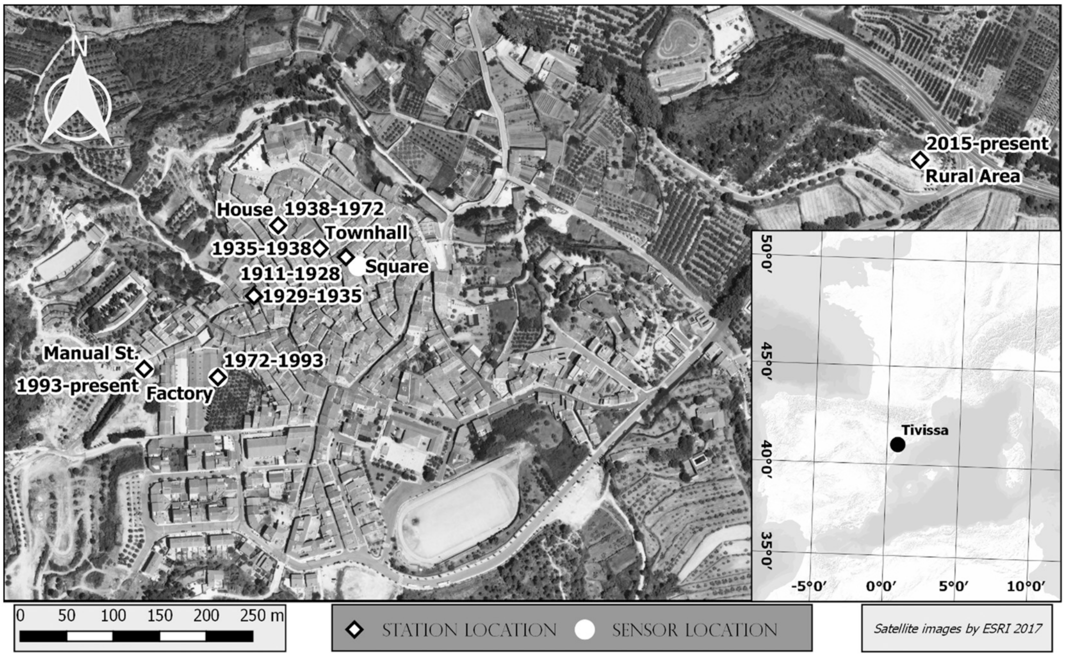

Fig. 1. Temperature measurements in Tivissa. Historical meteorological station sites with interval of operation and sensor placements close to these sites (main map). Location of the village in Spain (side map).

temperature records in Spain outside of the large cities. Saladié et al. (2013) worked on reconstructing the history of the meteorological station, which will be detailed in the following and refers to Table 1 and Fig. 1 regarding locations and measurement periods.

A Hellmann device for precipitation was installed after setting up the station in 1911 and a Tonnelot maximum and minimum thermometer to measure temperatures one year later (Jardí, 1923). Instruments have been protected with a screen ever since, being very similar to a Stevenson setup. The screen was replaced in 1972 by a new one of the same type. Apart from this change, several relocations took place during the course of the station's history. First, measuring started on the roof terrace of a building in approximately 7 m height above ground in the village centre (Roof 1). From 1929 to 1935, the station was situated 150 m away from Roof 1 in a similar location and was set up the same way (Roof 2), although this time a lawn was adjacent to the house in the North. A different site was chosen for the following three years, when measurements were performed on the flat roof of the town hall clock tower in a height of 15 m (Town hall). In 1938, the station moved to the roof terrace of a building again, very similar to the first two locations, where it stayed until 1972 (Roof 3). Until 1950, every relocation was coupled with a change in observer as well. In 1950, a change in observer took place but the station remained in the same place. The observer, head of a local company, moved the station out of the centre to his factory in 250 m distance to the previous site in order to insure better accessibility and maintenance 22 years later. Although todays' manual station is still located at the factory, it has experienced minor relocations within the factory before

Table 1
Station history and sensor locations. Information on the historical installation of the meteorological station as well as the placement of the recent sensor network.

Location		Site description	ALT	period
Met station	Roof 1	on the roof terrace of a house in the centre of the village	317 m	1912–1928
	Roof 2	on the roof terrace of a house in the centre of the village	317 m	1929–1935
	Town hall	on the clock tower of the town hall (approx. 15 m height)	318 m	1935–1938
	Roof 3	on the roof terrace of a house in the centre of the village	314 m	1938–1972
	Factory	mainly: on paved concrete slightly elevated, factory hall to the west and vineyard to the east; afterwards: several undocumented smaller relocations within the factory took place – placement somewhere between first location and manual station	318 m	1972–1993
	Manual Station	on lawn, some trees around, factory hall in 20 m distance	310 m	1993-today
	Square	on lamp post on square (20x10m), parking space nearby, three story buildings	301 m	From 2015 on
U23 sensors	Town hall	on metal post next to old met station location	318 m	From 2015 on
	House	on railing next to old station position (Roof 3)	314 m	From 2015 on
	Factory	on post where old station was located, now small olive trees to the east	318 m	From 2015 on
	Manual Station	in screen of current manual station	310 m	From 2015 on
	Rural area	on post of AWS, bare ground, some trees nearby as well as a road and a street	314 m	From 2015 on

moving to its final spot, most of the time being situated on an elevated concrete surface (3 m height) east of the great factory halls (Factory). Unfortunately, the dates of these minor relocations have not been reported. The final change was performed in 1993 with the station being relocated to a lawn west of the factory halls where measuring is still taking place (Manual Station), albeit the fact that an automatic weather station was installed east of the village in 600 m distance to the centre in 2015. Nowadays, the manual station is maintained by the former observers' son and is part of the network run by the Spanish Meteorological Service, while the automatic station is maintained by the Meteorological Service of Catalonia. Information on relocations and changes in observing staff is based on documents completed by the observers or members of the meteorological agencies, as well as derived from personal conversation with them. The temperature datasets along with metadata was provided by Meteorological Service of Catalonia.

The temperature data from Tivissa used in this study consists of a monthly minimum and maximum temperature record spanning from September 1912 to December 2016. The time series is continuous for 104 years, although a total of 17 months have been disregarded because of missing data. To detect UHI intensities related to the changing historical siting of the station throughout this period, a set of six sensors measuring temperature and relative humidity was installed in the village (Fig. 1 and Table 1). Even though the station moved three times within the centre from 1912 to 1972, it was only possible to install sensors in two of these locations: the top of the town hall clock tower (Town hall) and the roof terrace where the station has been situated from 1938 onwards (House). Being very similar to the later site, and very close as well, we estimate the first two locations to be well depicted by the one sensor placed on the roof terrace. Similarly, due to a lack of information on smaller relocations within the factory, and since the station was located east of the factory halls for most of the time, we chose this spot to be representative until 1992 (Factory). To depict the recent situation, one sensor was placed within the screen of the current manual station (Manual Station). An additional sensor was set up in the central square of the village (Square), trying to assess the presumably maximum UHI intensity in the village, while another one was placed outside the village at the current automatic weather station in order to serve as a rural reference (Rural area).

The sensors installed are of the same type and are protected by a radiation shield (HOBO Pro v2 U23–001 with RS1, Onset Computer Company), except for the one sensor located within the screen of the manual station. For analysis, daily mean (T_{mean}), minimum (T_{min}) and maximum (T_{max}) temperatures were derived from the dataset. Since the measuring interval was set to 30 min, the mean was calculated using the 48 daily values. T_{max} and T_{min} are the highest and lowest of the 48 daily values, respectively. Unfortunately, actual minimum and maximum temperatures might differ slightly because they could occur within these intervals. Monthly, seasonal, and annual temperatures are simple averages of the daily values and used for the correction at monthly resolution. The data of this observation campaign is comprised of two full years from October 2015 to September 2017.

With only two years of data serving as basis to correct long-term UHI influences, a frequency analysis serves to clarify whether the period is representative for UHI occurrence and intensity in the past. As cloud cover, wind speed, and relative humidity are correlated with UHI formation (Gedzelman et al., 2003), we use these parameters to compare the seasons within the 2-year-period with the seasonal data from the longest common period available, which is 1948–2017. Seasonal averages are calculated based on monthly relative humidity and wind speed data obtained from NCEP reanalysis data provided by NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, (https://www.esrl.noaa.gov/psd/) using the mean of the grid points surrounding Tivissa (0°E|40°N, 0°E|42.5°N, 2.5°E|40°N, 2.5°E|42.5°N), while monthly cloud cover data are obtained from ECA&D (https://www.ecad.eu/) using the mean of several stations in relative vicinity to Tivissa (Tortosa, Lleida, Reus, Calamocha, Castellon de la Plana).

2.3. UHI elimination

To assess the UHI in Tivissa and a possible impact on the long temperature record, a rural reference is crucial. The current AWS site was selected to host the reference sensor since it is located outside the village and should meet all requirements detailed by the WMO (2011) to serve as a representative site.

Correcting the long station record for potential impacts at different times requires splitting the time series in several segments according to its past locations detailed in Section 2.2. The temperature residuals were quantified considering the sensor network and removed from the original time series. In total, the meteorological station was installed at seven sites in Tivissa. The first two sites as well as the fourth were located in the centre of Tivissa on roof terraces being represented by the current sensor on the respective roof terrace. A correction factor at these locations was assessed by subtracting the daily mean, minimum and maximum temperatures measured in the rural area from the ones of the station locations ($T_{Location} - T_{Rural}$). Monthly, seasonal, and annual values were subsequently derived from the daily data. Since the rural sensor is assumed to be free of an urban influence, the resulting anomalies equal the site-specific anthropogenic impacts, with negative values suggesting a downward and positive values an upward correction of the original time series ($T_{Temperature\ record} + T_{Anomaly}$). The procedure was applied to all past locations and periods of the long station record including the town hall, factory, roof terraces and current manual station. Since all of the measuring sites are part of the urban area, the thermal properties are determined by anthropogenic materials. Addressing and adjusting the temperature differences of these locations with regard to a rural reference is a removal of anthropogenic warming influence – and hence an elimination of UHI intensity, while it is a correction for relocations at the same time.

2.4. Comparison with HOMER

The introduced procedure focussing on the removal of UHI influence, i.e. the relocation bias, is mainly dependent on two major elements. On the one hand, existing metadata has to be thoroughly investigated in order to precisely determine the past measurement sites and periods the meteorological station was located there. On the other hand, the site-specific climate needs to be recorded to determine the anthropogenic influence at the respective locations. The approach assumes an unchanged structural environment throughout the correction periods though. In contrast, statistical homogenization based on HOMER relies on additional station data from the region that the target time series could be compared with. Considering HOMER thus relies on the assumption that unbiased station data is available in the region. MeteoCat applied HOMER to homogenize the minimum and maximum temperature records from Tivissa. Since both, the station-location based approach and HOMER, aim to improve the dataset and mitigate UHI effects, it appears interesting to compare the corrected data and discuss the differences between an approach considering site meta information in more detail and an approach adjusting the data to the regional signal. Although technically not fully correct, since both approaches work towards the same goal, we will refer to our approach as a "correction" and the HOMER approach as a "homogenization" to avoid confusion.

The comparison was performed by first assessing the residuals for each year, considering the values being added or subtracted by the automated homogenization and the manual correction (chapter 2.4). In a second step, the residuals from the correction were subtracted from the ones produced by the homogenization. Due to the scarcity of other records before 1950, the homogenized data is only available from that year onwards, constraining the period of overlapping data to 67 years.

Since many studies focus on mean temperatures, we chose to include these as well by calculating the mean of T_{min} and T_{max}. However, this has only been performed for annual means. To emphasize longer term trends and changes, we smoothed the data using a 10-year spline applied to the original, homogenized, and corrected time series (Cook and Peters, 1981).

3. Results

We first address the spatial variations in Tivissa as well as the representativeness of the sensor dataset, particularly focussing on the UHI effect. UHI intensity will then be used to correct the dataset for relocation biases during different time periods. In the following, the corrected record is compared to the one produced through statistical homogenization relying on HOMER.

3.1. Spatial differences

To illustrate site-specific differences and the UHI intensity at all station locations, we calculated the differences using the rural sensor outside the village as a rural reference. Fig. 2 shows that inter-seasonal variance is very distinct in ΔT_{max}. The overall pattern reveals mostly higher temperatures compared to the rural area at all sites and is most distinct in summer (and spring) reaching a value of 1.8 K (1.2 K) at the factory site. A similar, but slightly weaker warming is detected at the square in the village centre. Both locations display strong discrepancies between spring/summer and autumn/winter ΔT_{max} that do not occur at any other location or parameter. In winter, the temperature residual for the square even falls below zero (−0.2 K). Seasonal temperatures on the roof terrace and at the manual station are not very different, rangeing from 0 K to 0.5 K, except for summer ΔT_{max} at the manual station reaching 0.7 K. The town hall temperatures are similar to the rural location (residual < 0.2 K) regardless of the season.

The spread in ΔT_{mean} is generally smaller compared to the other parameters, i.e. inter-seasonal as well as inter-sensor differences are less pronounced. Temperatures at the factory still display the largest seasonal variations, particularly during summer (0.7 K), with winter being the only negative anomaly in ΔT_{mean} (−0.2 K). As with ΔT_{max}, the sensors at the roof terrace and at the town hall show almost no seasonal differences. Overall, summer is again the season displaying highest residuals at all locations but the town hall, with a peak value of 1.1 K at the square.

All locations except for the factory show significantly higher seasonal anomalies in ΔT_{min} of at least 0.4 K. A unique feature in ΔT_{min} is found at the factory, displaying exclusively lower temperatures than the sensor in the rural area (−0.5 K over the entire year). There is less seasonality in T_{min} compared to the two other parameters, with differences < 0.4 K at each site, except for the factory. The square in the centre develops the most substantial warming with an anomaly of > 1.5 K during summer. The variance in the dataset for each location is higher in comparison to ΔT_{mean}, but similar to ΔT_{max}.

A frequency analysis was performed to evaluate whether the data recorded over the recent 2-year measurement campaign are representative for past UHI formation (Fig. 3). While wind speed during the campaign exclusively belongs to the upper third of data displayed here, and even includes one value among the highest ones (6.5 m/s), relative humidity shows no tendency or extremes, although the range is very distinct (38% to 70%). Seasonal cloud cover values recorded during the 2-year period also fall well within the range of all other years.

3.2. Eliminating the relocation bias

Since the spatial temperature analysis revealed distinct differences between the rural reference and the other locations, a correction of the long station record is necessary. The quantification of this spatial variability serves as the key to produce a Tivissa record free of relocation biases. Differences derived from the inter-sensor comparison were used for correction of the various time periods when the station was situated in different locations throughout the village, as shown in Fig. 4. A substantial downwards correction of > 0.5 K is applied over the first 60 years of the T_{min} record when the station was located within the centre of the village. For the same time period, the correction in T_{max} is considerably lower in all seasons, especially from 1935 until 1938 (town hall clock tower), when differences are close to zero. To account for the relocation to the factory in 1972, a strong downward correction is applied to T_{max}, while T_{min} is corrected upwards in order to account for the nocturnal cooling detailed in Section 3.1. From 1993 onwards, the current manual station was in use and, in consequence, the original temperatures are lowered again by about 0.5 K or less in T_{min}, though not as much in T_{max} except for a distinct correction in summer.

Correcting the > 100 year-long records affected the T_{min} and T_{max} time series differently, producing an increasing warming trend

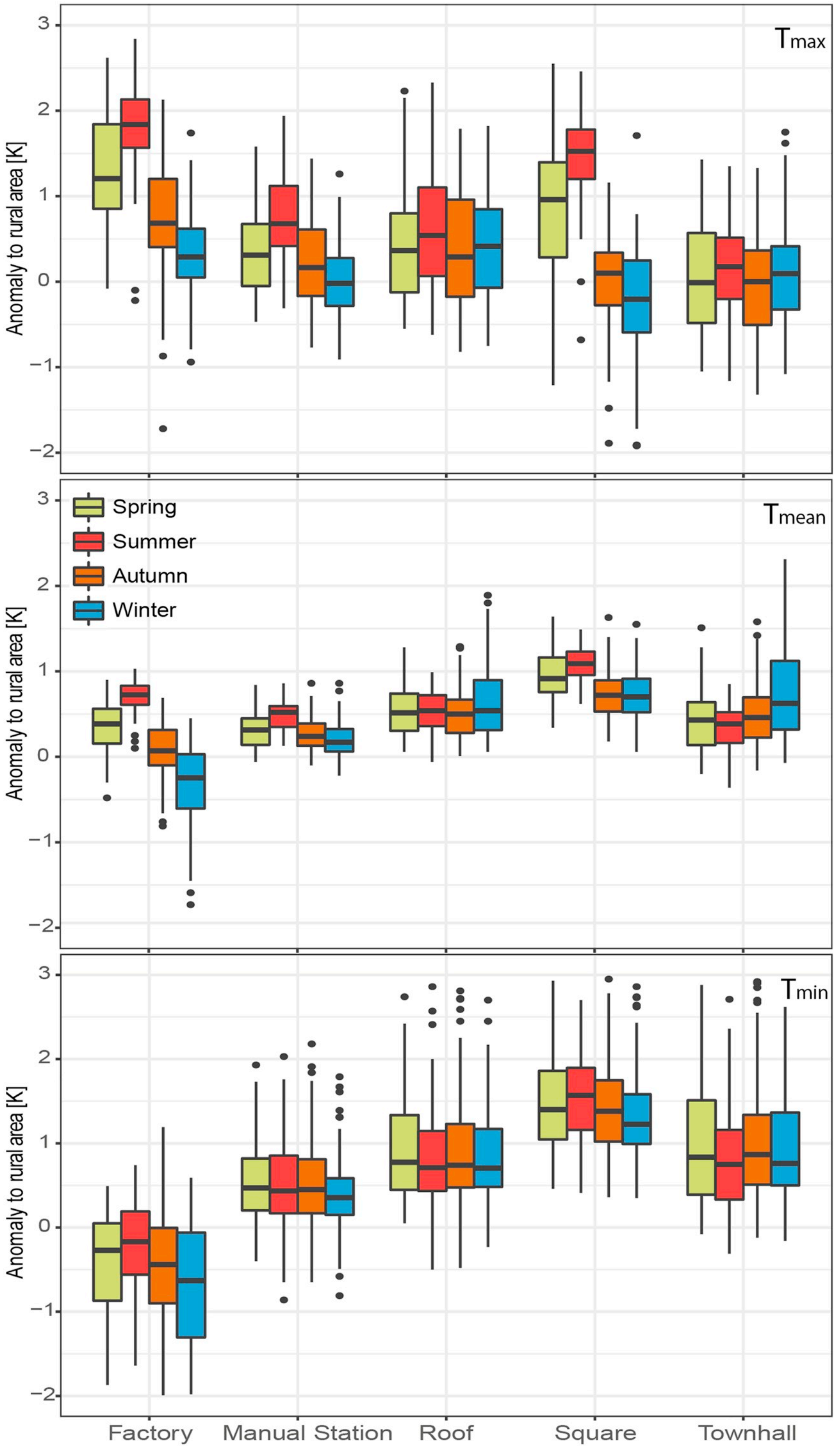

Fig. 2. UHI intensity in Tivissa. Seasonal maximum (top), mean (middle) and minimum (bottom) temperatures of all sensors displayed as anomalies with respect to the rural reference sensor (AWS) based on daily data. Boxplots display the median (black middle line), the upper and lower quartile including 50% of the data (coloured box) and whiskers (vertical lines) including the remaining 50%. Values beyond 1.5 times the interquartile range are plotted as outliers and are excluded from the whiskers.

in T_{min}, while the trend in T_{max} remained unchanged or was reduced compared to the original data (Fig. 5). Before correction, T_{min} trends were not very distinct except for summer (0.08 K/10 years). The correction increased the warming trend to above 0.1 K per decade in all seasons, a doubling or more compared to the original data. This is especially true for winter, where the correction causes

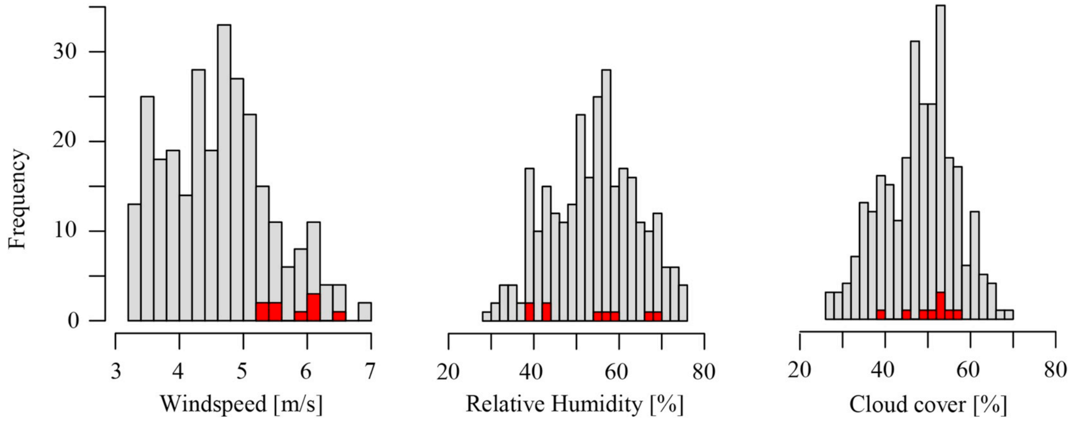

Fig. 3. Representativeness analysis. Grey bars indicate the distribution of seasonal wind speed, relative humidity, and cloud cover data for the last 70 years. The values recorded over the 2-year measurement period are shown in red. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

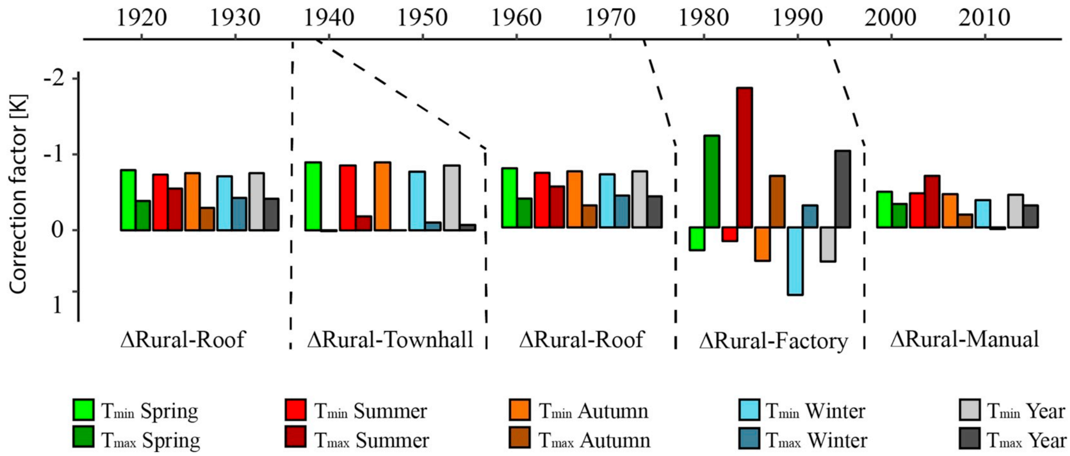

Fig. 4. Time series adjustment. Corrections applied to the minimum and maximum temperature series according to the different measuring periods.

a tenfold trend increase, from 0.01 to 0.11 K/10 years. Although summer T_{min} was least affected, it displayed the strongest overall warming. While the warming was most pronounced in summer for T_{max} as well (0.21 K/10 years), the correction substantially reduced this trend to 0.14 K per decade. Summer temperatures were thus most affected by the correction. A slight downwards change of trend lines occurred also during spring and autumn, although the original and corrected trends patterns remained almost the same in autumn. Overall, uncorrected warming trends were far stronger in T_{max} than in T_{min}, but the correction resulted in aligning these trends by enhancing T_{min} and reducing T_{max}. Winter T_{max} is an exception since the original trend was increased during correction, from 0.13 K to 0.17 K.

3.3. Comparison of correction and homogenization approaches

In order to assess the differences between the relocation bias correction introduced here and the widely applied statistical homogenization, both the corrected and homogenized records are plotted along with the original time series in Fig. 6. The dashed lines mark the years when relocations took place.

In general, the homogenized dataset is characterised by a stronger downwards adjustment in T_{min} and mostly upwards one in T_{max}. The biases indicated by the two methods are often reversed, i.e. where homogenization resulted in higher temperatures, correction caused a cooling, and vice versa. However, the changes applied to the original dataset show some agreement between homogenized and corrected record until 1972 and from 2009 onwards. In-between, the severe change in the homogenized dataset results in a discrepancy of approx. -2 K between the homogenized and corrected versions for many years and peak values of more than −3 K in 1991/1992, although decreasing one year later. In summer T_{max}, the corrected time series displays lower temperatures for the whole period while the homogenized data shows the opposite until 1984. The corresponding differences are almost constantly ~0.7 K until 1973 and from 1997 onwards, due to the more positive adjustment in the corrected record. Within the 20 years from 1972 until 1992, this discrepancy is much more pronounced with values reaching ~4 K. This is particularly true for the years around

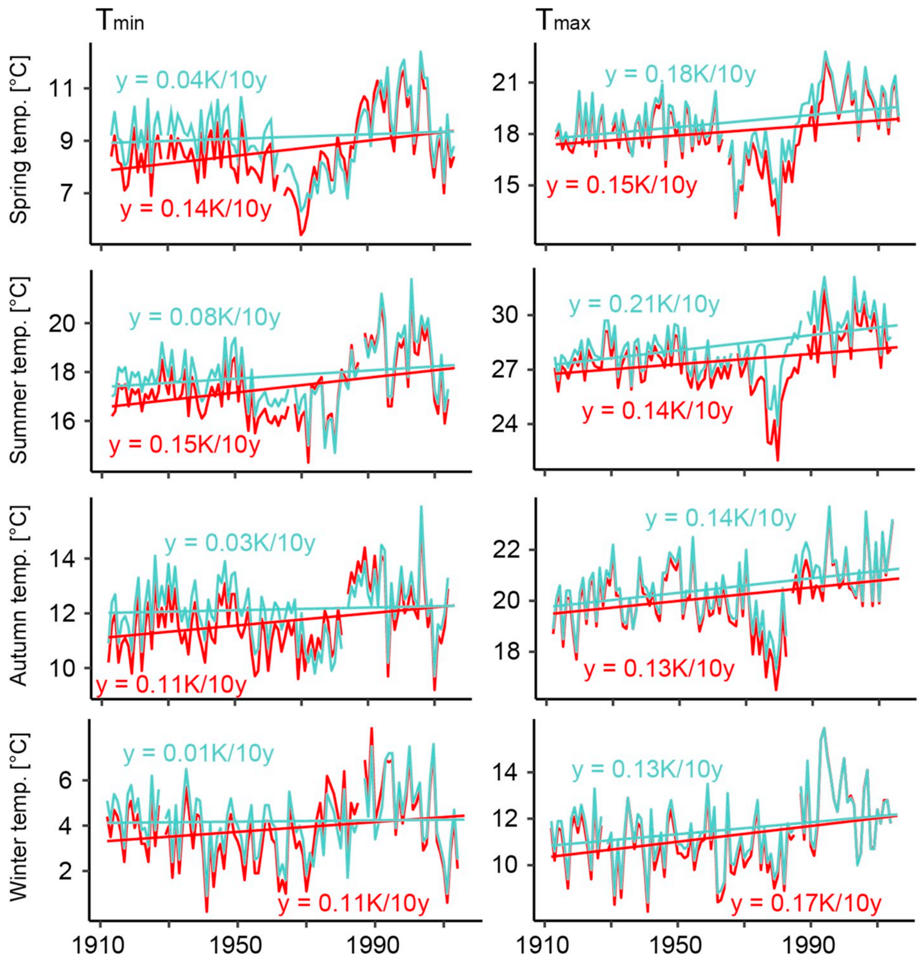

Fig. 5. Trend changes after adjustment. Original (turquoise) and corrected (red) seasonal temperature time series and the corresponding decadal trends from spring to winter derived from linear model. Minimum temperatures are displayed in the left column, maximum temperatures in the right. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

1980, when original data show a distinct cooling that is still visible in the corrected record, but was almost fully removed during homogenization in order to match the higher temperatures of the regional signal. Although the overall pattern in winter is more similar, other features evolve. While the difference between the correction values is stronger in the beginning (~ 1 K), it lasts until 1975 and is less pronounced thereafter, though never exceeding 2.1 K. Differences are almost negligible from 1984 to 1989 as well as after 1997, but a substantial downwards correction in the homogenized record causes the values to drop (~ 1.5 K) temporarily in the beginning of the 90's.

Since many studies focus on the development of mean temperatures in the 20th and 21st century, Fig. 7 details the differences between homogenization and relocation elimination on the yearly average time series. A 10-year spline was applied to emphasize long-term variability. The corrected record continuously stays below the original one since mean temperatures are biased by UHI formation throughout the whole record. The difference is stronger in the beginning (~ 0.5 K) and reduced towards recent times (~ 0.3 K), leading to an increase in warming trend in the corrected data. The general pattern of the temperature record is not changed when correcting the relocation biases. However, the application of HOMER introduces distinct changes of the overall pattern. While showing good agreement with the corrected record over the early years, a drastic change is observed from the late 1970s until the beginning of the 21st century, when the homogenized values first overshoot the cooler period in original and corrected record by 0.5 K and more, but later undershoot these by ~1.5 K around 1990. These differences result from the steep temperature increase in the original dataset during the 1980s, a feature that the homogenization procedure mitigated by replacing it with an extended though reduced warming trend. In recent years, the homogenized and original data are almost the same.

4. Discussion and conclusions

In this chapter, we first discuss the observed temporal and spatial variability in urban microclimates in Tivissa. Subsequently, we discuss and evaluate the implications our correction has for the Tivissa temperature record and address the partly substantial

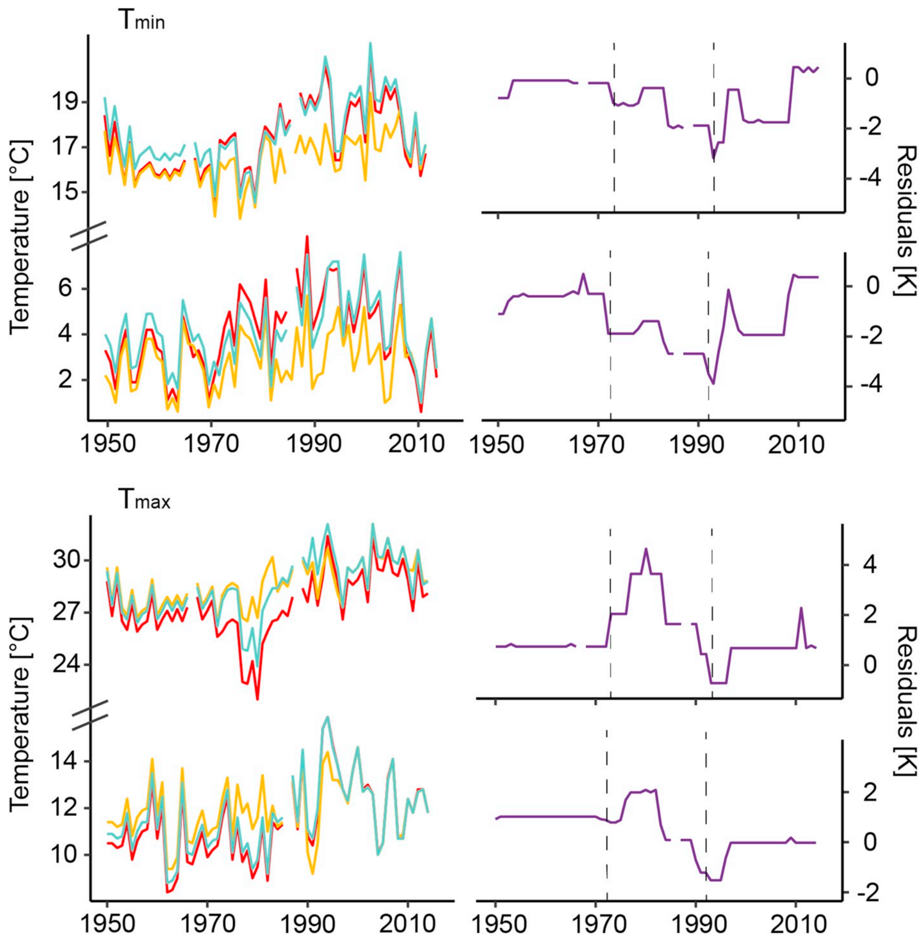

Fig. 6. Adjustment differences. Summer and winter Tmin (top) and Tmax (bottom) after correction (red) and homogenization (orange) shown together with the original time series (turquoise). The residuals (ΔCorrValue correctedTS-homogenizedTS) are displayed in the right column. The dashed lines indicate relocations. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

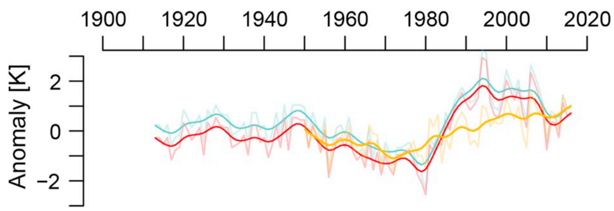

Fig. 7. 20th century trend comparison. Annual mean anomalies of the original Tivissa record (turquoise) along with the corrected (red) and homogenized (orange) series. All records are shown as anomalies with respect to the original series reference data from 1950 to 1959. The thin curves show the absolute values while the thick curves are 10-year smoothing splines.

differences compared to the homogenized time series.

4.1. Urban warming in Tivissa

The Spanish village Tivissa (< 2000 inhabitants) was found to develop an UHI that is most pronounced in summer and least in winter, but detectable in almost every season and parameter examined in this study. This finding is not in line with other evidence from the Mediterranean claiming the UHI intensity to be strongest in winter (Montavez 2000; Papanastasiou 2011). A further investigation has to be carried out in order to explain this discrepancy.

The square in the village centre is most affected by urban warming, with summer temperatures revealing a difference of > 1 K in ΔT_{mean} and 1.5 K in both ΔT_{min} and ΔT_{max}, if compared to the rural reference. These intensities are comparable to UHIs found in larger cities such as Utrecht (300,000 inhabitants) with a nocturnal UHI of 1.5 K (Brandsma and Wolters, 2012), Manaus (2,000,000 inhabitants) with 0.7 K and 1.6 K in summer T_{min} and T_{max}, respectively (de Souza and dos Santos Alvalá, 2014), Chennai (4,700,000 inhabitants) with 2.5 K (Devadas and Rose, 2009) or Volos (200,000 inhabitants) with 2 K mean maximum UHI intensity in summer (Papanastasiou and Kittas, 2012). However, other cities like Seoul or New York show much higher maximum intensities with 3–4 K on average in a year (Gedzelman et al., 2003; Kim and Baik, 2002). Low sky view factors and hence radiation trapping usually contribute to additional warming in densely built areas (Hamdi and Schayes, 2008), same as anthropogenic heat sources (Pigeon et al., 2007), but UHI intensities observed at the central square in Tivissa, especially in ΔT_{max}, are comparably small in autumn and winter. Since regional wind activity as well as cloud cover are increased (European Climate Assessment & Dataset, https://www.ecad.eu) and the sun shines from a lower angle during wintertime, higher wind speeds and stronger urban shading effects likely mitigate the UHI intensity as also reported by Morris et al. (2001) and Emmanuel et al. (2007).

Other sites show interesting differences as well. In ΔT_{max}, almost no UHI formation is detectable at the town hall site. Since the sensor is positioned on top of the clock tower and above roof-level, winds are stronger compared to lower levels in the urban area (Nakamura and Oke, 1988), thus likely mitigating heating through accelerated ventilation as also described by Ramponi et al. (2014). The large variance, with lowest nocturnal temperatures and among the highest daytime temperatures, found at the factory site are likely caused by a complex combination of underlying processes. The sensor was placed above a concrete platform with a paved surface covered by a roof, and the factory buildings to the West and a small field of low trees, formerly a vineyard, to the East. Low heat capacities of stone, concrete and metal accelerate warming during daytime when solar radiation is highest, but contribute to a rapid cooling after sundown, thus contributing to high T_{max} and low T_{min}. In addition, nocturnal anthropogenic warming is likely negligible because activity at the factory stops at night. Since spatial and temporal differences in hilly and mountainous terrain are often caused by local topography and climatology, e.g. cold air flows as described by Barry (2008) or Poulos and Zhong (2008), the factory site might be affected by this. As the terrain slopes westwards, cool downhill air flows are trapped at the factory buildings within the roof-covered area that is open to the East. During the day, ventilation is presumably impeded which amplifies warming. Although the manual station sensor is only about 50 m away, it displays a completely different pattern. Here, the overall UHI intensity is low but not negative, with ΔT_{min} amounting to almost 0.5 K in all seasons but winter. The open placement on a lawn with some distance to urban structures minimizes warming influence, while at the same time preventing a pooling of cold air as the terrain slopes further westbound.

Given the intensities of the UHI in Tivissa, these findings signify the need to treat villages as urban areas instead of being a part of the rural landscape. Village warming is more intense in T_{min} than in T_{max}. This is in line with many findings from all over the world (e.g. Kim and Baik, 2002; Klysik and Fortuniak, 1999; Wilby, 2003). Substantially lower inter-seasonal differences in T_{min} compared to T_{max} imply a strong decoupling of nighttime UHI intensity from seasonal influences.

4.2. Implications of time series adjustment

The UHI effect found in Tivissa at all examined locations confirms the need to correct for anthropogenic warming incorporated in the dataset by accounting for station relocations. Since all past locations of the meteorological station are characterised by particular microclimatic conditions, the record was adjusted in accordance to the historical placement of the Tivissa station. We here refer to the correction of warm bias as an elimination of the relocation bias rather than a removal of gradual warming caused by the growth of a city as addressed by Jones et al. (2008) or Fujibe (2011). However, some degree of uncertainty is added to the correction factors as the study relies on a 2-year measurement campaign to identify UHI intensities that should be applicable for the whole record, actually spanning > 100 years. Judging from the results of the frequency analysis of meteorological parameters related to the UHI intensity (FF, RH, CC), relative humidity as well as cloud cover during the measurement period are perfectly in line with the majority of the other years considered here. Since wind speed during the 2-year campaign showed a tendency towards higher velocities, UHI might have been even slightly more intense in the past as higher wind speeds generally lower the UHI intensity (Kim and Baik, 2002; Morris et al., 2001).

For T_{min}, the correction resulted in a substantial rise in warming trend over the last > 100 years. Although urbanization effects likely have a minor impact on temperature records at large spatial scales (Jones et al., 1990; Peterson et al., 1999), the elimination of anthropogenic influences leading to an increased warming trend is confirmed by other studies from Northern Scandinavia (Tuomenvirta, 2001) and China (Yang et al., 2013). The reason for this trend amplification is found in the movement of the meteorological station and its historical placement in Tivissa. Initially located within the village and hence influenced by urban warming effects, a stronger downwards correction had to be applied in the beginning. The placement in the factory in the 1970s led to an inverse correction since accelerated cooling at night compared to the rural reference made an upwards adjustment inevitable. Although the station moved to the current manual station location 20 years later, which resulted in a downwards correction again, the UHI affecting the measurements is smaller compared to the first locations. Zhang et al. (2014) point out that this increase in warming trend might as well be caused by a recovery of the urban warming related to the steady growth of an urban area that would otherwise be mitigated by the relocations to less urbanized areas towards present. However, we estimate this to be very unlikely in Tivissa, because population has declined rather than increased from 1910 onwards and only small changes have occurred regarding building structure within the last 100 years.

Correcting for the relocation bias generated less change in the T_{max} than in the T_{min} trend, with the exception of correcting for the microclimate at the more recent factory site. The strong downwards correction in T_{max} for the time when the station was located at this site even caused a decreased trend in spring and summer. Since the factory site seems to be of great importance to the correction and the resulting warming trend, a follow-up study needs to further clarify the site-specific climatology and provide a better insight into daily cooling and warming patterns. Nevertheless, a strong increase in warming trend for T_{min} and less distinct patterns in T_{max} are similar to recent findings from a long-term temperature record in a Swedish village (Dienst et al., 2017), and emphasize the need to re-evaluate warming trends in meteorological data from village stations.

4.3. Evaluating the correction approach

From 1950 onwards, the Tivissa time series has been homogenized by means of the widely used HOMER script, enabling a comparison of both methods. Since the homogenized and corrected time series revealed substantial differences, a closer look on the varying patterns is inevitable in order to understand the reasons for this discrepancy and evaluate the strengths and weaknesses of both approaches. Considering T_{min}, a good agreement between homogenized and manually corrected records was found in the early station period, with both approaches suggesting a downwards correction of the original record. For the 20 years when the station was located at the factory, the two approaches produce different results, with our correction adjusting cooler conditions and the homogenization removing an assumed strong impact of non-climatic related warming. The erratic residuals during that time originate from changes in the correction factor suggested by homogenization. Since it is known that the station had undergone minor relocations within the factory, a varying correction factor supposedly better addresses this time interval. As a result, the factory sensor might be representative for most time but not the entire period. However, there is no indication for a strong downwards correction as suggested by homogenization either, because not only the factory site data contradict that finding, but also the data gathered at the current manual station. The latter are recorded close to the factory and show only small warming influences. In addition, no changes to the screen were applied during this time that might explain a strong amplified warming. Hence, we advise against the results obtained from homogenization during this period. Nevertheless, since the discrepancy is strongest around 1980, a solely short-term inhomogeneity is still the main reason for this offset. Besides, the strong adjustment in homogenization persists after 1993, when the station was moved to the current location (manual station), but becomes insignificant after another 15 years. Since conditions have not changed since 1993, we consider our correction to be more reliable from that year onwards as there is no evidence to support a change in correction factor. Finally, an urban warming influence is still present at the current manual station site that is not captured in the homogenized data.

As the assessment of historical station sites indicate enhanced warming in only T_{max}, our correction lowers the overall temperatures of the dataset. Statistical homogenization agrees after the mid-1980s with this correction, but suggests an upwards adjustment prior to this. Again, evidence to support the alteration suggested by homogenization are lacking in the metadata, especially since possible impacts such as insufficient sheltering would result in a rise in T_{max} and hence imply an inverse adjustment (Brunet et al., 2006a). Additional ventilation at the roof terrace, as explained for the clock tower in Section 4.1, might have lowered T_{max}, but sensor measurements instead indicated a slight warming to be present in some seasons nonetheless. Similar to T_{min}, the 20 years of measurements within the factory cause large discrepancies between the correction and homogenization approaches, potentially linked to the poorly documented station movements within the factory. Homogenization considers the bias in T_{max} after relocating the station to its current spot to be negligible, and while we agree this is correct for winter, an urban warming influence is still present in summer. In addition, homogenization does not capture the relocation in 1993 as the time series is adjusted several years later.

The corrected record reveals a warmer period in the 1980s following a prolonged period of lower temperatures that has not been removed by means of relocation bias elimination. In general, global temperatures depict this pattern as well (Hartmann et al., 2013). The general temperature decrease, starting in the 1950s, has been associated with a reduced incoming solar radiation due to higher aerosol concentrations caused by anthropogenic air pollution (Wild et al., 2007; Wild, 2009). These studies trace the strong increase in the 1980s back to the introduction of filters used in power plants, industrial production, traffic, and other devices that have reduced this impact, allowing the warming trend caused by increased greenhouse gas emissions to stand out again. However, the temperature increase of > 2 K in one decade as found in Tivissa, even if to some extent reasonably caused by a distinct drop in T_{max} before, is unlikely, since such a drastic change in climate is not retained in other records from Spain (see Brunet et al., 2006b). This unusual feature, however, seems not to be related to relocations, changes in sheltering or observer, so that we cannot report reasons for this phenomenon. Regardless of the cause, statistical homogenization with the HOMER method removes this increase and hence indicates a warming since 1980 similar as seen in other Spanish temperature series. Nevertheless, a cooling in T_{max} during the aforementioned period is supported by data from the nearby station in Reus (Centre de Lectura), which is located 30 km NE of Tivissa. The distinct pattern could therefore be, at least partly, attributed to an anomaly in local climatology, such as a change in the prevalence of slope wind systems that is not depicted on inter-regional scales.

The differences in adjustments are alarming, and while the approach presented here better considers the station history and offers a more site-specific correction, it struggles to correct for a presumably biased period in the 1980's, which is likely more properly addressed in adjustments by HOMER. However, timing and magnitude of correction factors derived from statistical homogenization methods are questionable and need to be validated if local climatology differs from the regional signal. Apart from that, homogenization is only applicable if sufficient reference records are available in the region. While this is true from 1950 onwards, our method is capable of improving the data before that time when only few or no regional climate data are available.

Declarations of interest

None.

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