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Homogenization of a combined hourly air temperature dataset over Romania

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Highlights

- Homogenized hourly air temperature datasets over Romania and its surrounding has been created
- Four quality control tests helped to identify and eliminate raw errors from the data
- The *Climatol* homogenization method was used to identify and correct the suspicious values

Abstract

Daily and sub-daily homogenization of climate variables have been intensively investigated in the last decades, but to the best of our knowledge, this is the first study on homogenization of hourly temperature in Romania. This paper describes the creation of a homogenized hourly air temperature data set at a country scale by combining data from four independent meteorological networks. The air temperature measurements for the period 2009 and 2017 were obtained from the following networks: Romanian National Meteorological Administration (ANM), National Network for Monitoring Air Quality (RNMCA), Regional Basic Synoptic Network (RBSN), and Meteorological Terminal Aviation Routine Weather Report network (METAR). The climatological limits, persistence, temporal variation (step test), and spatial consistency were the quality control tests used to isolate the errors due to malfunctioning of the temperature sensors, data coding or transmission. The *Climatol* homogenization method was successfully applied for identifying and correcting any suspicious values. The missing data were filled by considering the similarities between each station and the reference series. Comparing the output with the original data, it is apparent that the removal of the breakpoints, correction and

homogenization resulted in a new data set with statistical properties very similar to the raw data, but more reliable for climate research due to the increased homogeneity. Eventually, the procedure can be implemented in operational use for collecting more data from other networks.

Keywords

homogenization, hourly air temperature, R Climatol, Romania

1 Introduction

The wellbeing of most human communities is nowadays very much linked to ecosystem and climate services. Many applications intensively use meteorological information and their quality is crucial for the value of the results, so that consistent efforts for aggregating as much data as possible are constantly made. Temporal and spatial discontinuities are addressed by dense monitoring networks, data recovery and gridding techniques. Climate monitoring utilises benefits arising from technological progress and valuable data are currently collected from ground-based or remote sensors. In the recent decades, the accuracy of data has improved, the retrieval and manipulation are easier than ever and a variety of sources provide useful meteorological information, often in near-real time. However, the quality and homogeneity of the data should be permanently secured in order to differentiate the natural bias from the errors which are anthropogenic in origin present in climate variability. Air temperature is an essential climate variable that characterizes the heating or cooling state of the atmosphere measured in the immediate vicinity of the ground (Jarraud, 2008). Air temperature plays an important role in all socio-economic activities and it is the main triggering factor for meteorological and environmental processes. For climatic studies, it is always preferable to use data provided by dense meteorological networks, and all reliable data sources have to be considered (WMO 2007). Therefore, the quality of datasets is directly influenced by different standards of measurements and instruments, and the assimilation of the data in a quality checked, harmonized and homogenized set is needed.

Meteorological observations may also be affected by events unrelated to spatio-temporal variability specific to weather phenomena (i.e. errors in measuring or transmitting). Independent of unbiased weather and climate variability, changes in the measuring instruments, and in the location or the surroundings of the stations represent another category of factors that can influence meteorological measurements (Aguilar et al., 2003). Findings of meteorological and climatic studies may be distorted when they are based on datasets that contain inhomogeneities. Therefore, in order to reduce or eliminate the false signals from the climatic data series, several methods of homogenisation have been developed (Venema et al., 2012).

The increasing number of professional and amateur weather stations which provide meteorological information at high spatial and temporal resolution (i.e. sub-daily data), make fully automatic quality control (QC) and homogenization methods an essential tool for identifying and removing spurious measurements, as well as for adjusting the inhomogeneities from the series (Napoly et al., 2018; Hunziker et al., 2018). Numerous air temperature homogenization studies have been dedicated to monthly and daily data, including extremes, and focusing mainly on local and country scales. The COST Action ES0601 - Advances in homogenisation methods of climate series: an integrated approach (HOME) - implemented through 2006-2011 boosted the understanding of need for homogenized climate series and various homogenization methods targeted increasingly finer temporal scales for different regions. Some recent publications can be acknowledged as relevant for this study. Kolendowicz et al. (2018) used Alexanderson's Standard Normal Homogeneity Test to reconstruct the 169-years air temperature measurements available at Poznan, Poland. Osadchyi et al. (2018) applied HOMER approach to improve the quality of the monthly air temperature dataset collected in Ukraine from 178 stations between 1946–2014. Hewaarachchi et al. (2017) developed a methodology to homogenize in an efficient manner the daily temperatures, which uses along metadata and reference series, the seasonal cycles and autocorrelation. Shen et al. (2018) employed MASH method to correct the homogeneity of the daily data used for a quantitative assessment of climate change in North China. Homogenization of extreme air temperature was recently applied on the ECA&D series, by using the quantile matching approach (Squintu et al., 2018). Gubler et al. (2017) performed four experiments on Peruvian and Swiss networks in order to assess the influence of station density on climate data homogenization.

The main objective of this work is to create a homogenized hourly air temperature dataset over Romania, by aggregating measurements from different sources covering the country and its surroundings. Previous studies related to the homogenization of air temperature over Romania have tackled data at a monthly and daily scale, and they used only the measurements of the national meteorological network (Cheval et al., 2014; Dumitrescu & Birsan, 2015). To the best of our knowledge, this is the first study which focuses on hourly air temperature data and integrates data from several networks.

This paper is organized via introduction and 5 subsequent sections as follows: section 2 describes the type and sources of data investigated here; section 3 presents the methods to perform QC and homogenization; the findings of this work are presented in section 4, and thoroughly discussed and concluded in sections 5 and 6.

2 Data

Hourly air temperature data available between 2009-2017 on the territory and in the immediate vicinity of Romania have been selected from four data sources, as follows: Romanian National Meteorological Administration Network (Administrația Națională de Meteorologie - ANM), Romanian National Air Quality Monitoring Network (Rețeaua Națională de Monitorizare a Calității Aerului - RNMCA), Regional Basic Synoptic Networks (RBSN) and Meteorological Aerodrome Report Network (METAR).

The ANM network consists of 161 meteorological stations measuring the essential climate variables. Observations are carried out according to methodologies established by the World Meteorological Organization (WMO).

The National Network for Monitoring Air Quality (RNMCA) comprises 142 stations equipped with automatic instruments for measuring concentrations of the main atmospheric pollutants, from which 117 RNMCA stations measure air temperature, relative humidity and wind speed and direction at hourly frequency. Both atmospheric pollutant data and meteorological measurements can be accessed in real time on the Air Quality website (http://www.calitateaer.ro), managed by the Ministry of Environment.

Weather stations located at airports, military bases, and other sites perform measurements of meteorological parameters (air and dew point temperature, wind direction and speed, precipitation, cloud cover and heights, visibility, and barometric pressure), at an hourly and sub-hourly frequency, to ensure the safety of air traffic. These measurements are available in near-real time through the Global Telecommunications System (GTS), using the METAR standardized format (WMO, 2008).

Regional Basic Synoptic Networks (RBSN) is a component of the Global Observing System (http://www.wmo.int/pages/prog/www/OSY/Gos-components.html) comprising more than 4900 stations, exchanging data globally in real time using GTS (transmission completed 30 minutes after each synoptic observation hour). Meteorological data are freely available and unrestricted to use according to the WMO data policy agreed in Resolution 40 (http://www.wmo.int/pages/prog/hwrp/documents/wmo_827_enCG-XII-Res40.pdf).

The METAR and RBSN hourly data were obtained by using *rnoaa* (Chamberlain, 2019) an R language (R, 2018) interface to several NOAA data sources, including the Integrated Surface Database (ISD), which store global hourly and synoptic observations collected from numerous sources (Smith et al., 2011).

Air temperature data and metadata from 354 meteorological sites (ANM 161 stations, RNMCA 117 stations, METAR 5 stations and RBSN 71 stations) were collected for this study, securing a very good geographic distribution over Romania and neighbouring regions (Figure 1).

Figure 1 Spatial distribution of the selected weather stations (ANM, RBSN, METAR and RBSN).

Table 1 presents a summary of the data completeness by source. Analysing the availability of hourly measurements, it can be seen that from the total of 27,926,352 possible values (354 stations * 78888 hours) along the period 2009-2017, 7,067,118 hourly air temperature values are unavailable due to various causes (e.g. sensors fault, transmission errors, etc). Compared to the total number of possible values, the fewest missing values were found in the ANM database (7.9%), and the most in the RBSN database (63.0%).

Table 1 Availability (%) of the hourly air temperature data from the four networks used in this study

3 Methods

3.1 Quality control

The use of different types of instruments, procedures and standards for performing measurements as well as the training and professional quality of the personnel determine the quality of the meteorological data. Virtually all the air temperature measurements used in this study were retrieved by automatic instruments, but the merged dataset still comprises visible outliers (Figure 2) which requires the application of QC procedures prior to homogenization.

Figure 2 Hourly air temperature merged from four measurement networks (all stations). The spatial median across all stations is shown in red.

Four automated data QC tests were performed in order to assess the quality of the hourly air temperature measurements (Estévez, Gavilán, & Giráldez, 2011), namely: climatic limits consistency (Cheng, et al., 2016), persistence (Schroeder, et al., 2005; Zahumenskỳ, 2004), step (Lott, 2004) and spatial consistency test (Shafer, et al., 2000).

Climatic limits test if the hourly observed value is lower or higher than the specific climatological thresholds for the area analysed. Monthly multi-annual maximum and minimum air temperature obtained from the National Meteorological Administration Network computed for the period 1981-2017 were used as thresholds. The persistence test checks the largest difference between observations within a moving time range (24 h). If the difference is less than a maximum acceptable change (0.1°C), all the values of that parameter for the station under consideration are flagged as questionable. The stepwise test verifies the differences between the current value (T_i) and the previous one ($T_i - 1$) and between the current value and the following one ($T_i + 1$). If the computed values met the following criteria, the air temperature values were excluded from further analysis: $|T_i - T_{i-1}| > 8°C$ and $|T_i - T_{i+1}| > 8°C$. The spatial consistency is performed on the hourly air temperature data by the using Regression Kriging (RK) spatial interpolation method, using elevation as auxiliary variable. The true values (T_i) and expected values (Z_i) of the hourly air temperature are compared by using the following criteria: $(T_i - Z_i) \,/\, \sigma_i > p$. If the differences between the two values exceed certain threshold (p), the observed values are removed from the analysis.

3.2 Homogenization

The homogenisation and data filling of the hourly air temperature dataset were performed using version 3.1.1 of the R package climatol: Climate Tools (Series Homogenization and Derived Products). This library can be freely installed on R from CRAN package repository (https://CRAN.R-project.org/package=climatol, last accessed 15 February 2019). Beside meteorological records, *Climatol* uses various stations metadata such as longitude, latitude and altitude (Guijarro, 2018).

The *Climatol* method has been successfully used to homogenize air temperature data (Mamara et al., 2013; Kolendowicz et al., 2018), solar radiation (Sanchez-Lorenzo et al., 2015), wind speed (Azorin-Molina et al., 2018), wind gusts (Azorin-Molina et al., 2016; Azorin-Molina et al., 2018) and precipitation (Luna et al., 2012). *Climatol* was also tested against realistic benchmark datasets and returned very good results comparable to other homogenization methods which are currently used by the climatology community (Venema et al., 2012; Guijarro et al., 2017).

The *Climatol* method normalizes the time series, and the significant shifts (break-points) are obtained by running the SNHT test on differences between the observed data and computed reference series. Due to the high spatio-temporal variability of the hourly air temperature imposed by the mountain topography, the homogenisation was performed first on the aggregated time series at a monthly scale, and the break-points detected on monthly data were used to split hourly values in homogeneous sub-periods, further adjusted and gap-filled by the routines implemented in *Climatol.*

The QC procedure retrieved many errors in the RNMCA archive. Since the results of the homogenization can be strongly influenced by the quality of the time series, we decided to perform the procedure in two steps: 1) homogenization of the subset with higher quality, including the ANM, METAR and RBSN data, and 2) apply the homogenization on the combined dataset (data homogenized in the first stage, and the raw RNMCA dataset).

4 Results

4.1 Quality control

Following the quality control procedures, gross errors were identified and eliminated from the further analysis. Such errors refer either to malfunctioning of the temperature sensors, i.e. transmission of the same value for a long time, or to large variations in measurements between at least two consecutive hours (Figure 3). Cheval & Dumitrescu, (2017) demonstrated that the thermal difference between consecutive hours very rarely exceed 4°C in an urban environment, even if higher variations may occur naturally. Possible errors were also reported when the measurements do not fall within the common range of the spatial temperature variation, according to the measurements of the closest 30 meteorological stations. Quality control should always precede the homogenization procedure in order to obtain a realistic dataset with large spatial coverage.

The seasonal histograms show that the distribution of the quality-controlled dataset is close to a normal distribution, without extreme values located far apart from the other observations (Figure 4).

Figure 3 Quality-controlled and corrected hourly air temperature merged from four measurement networks (all stations). The spatial median across all stations is shown in red.

Figure 4 Seasonal histograms of the quality-controlled and corrected hourly air temperature merged from four measurement networks (all stations).

4.2 Homogenization

The *Climatol* homogenization procedure is based on the use of break points detected at monthly scale for correcting data series at finer temporal scales for each station, and Figure 5 provides a clear illustration for Szolnok (Hungary), close to the western border of Romania. This station was selected due to the most suggestive results provided consistent with all the elements shown in the graphs from Figures 3 and 4. The monthly anomalies (left) shows that the shift in the monthly mean series has been detected for a SNHT value corresponding to 31, i.e. September 2012. The two lines at the bottom of the break point detection graphs inform about the minimum distance of neighbour data (in green) and the number of reference data (in orange). For these additional lines, it is used a logarithmic scale on the right axis. The annual running mean of the reconstructed time series is provided in the plot of the right side of the panel. The corrections applied to each time series are displayed in different colours at the bottom of the same graph, while a black line is used for the original time series.

For each station time series, we have selected the reconstructed series containing the higher POD (percentage of original data), because a bigger number of original data in the series will make its adjustment more reliable. The *Climatol* method excluded from the analysis the data from the stations with a high percentage of missing data. The application of the monthly homogenization method resulted in a selection of 294 stations out of the 354 initial sample. While the data from all the stations are filled during the homogenization of hourly data (i.e. stage 2 of the procedure), five stations still have a high percentage of missing data, and they were removed from the hourly homogenization.

The number of splits detected per year and data source is very small, which can be explained by the limited period analysed in this study (i.e. from 2009 to 2017) and by the high level of standardization employed by the measurements. Most of the splits were detected within the ANM database (Table 2), and they are entirely due to the change in the instrumentation, from classical to automatic weather stations.

Table 2 Number of break points detected within the four networks used in this study.

The results and improvements in the quality of time series due to homogenization are analysed by comparing the statistical properties between original and homogenized data. The standard deviation values computed for each day and station in the two sets of data were compared by using box-plot diagram. The ranges of standard deviations obtained from the homogenized data are lower for all years as a result of removing the breakpoints and adjusting the data series (Figure 6). However, the annual medians (marked by the horizontal black line inside the rectangles) have not changed significantly, being almost identical for all years, with small differences noticed in 2016 and 2017.

Figure 5 Example of break point detection (left) and the two time series reconstructions from both homogeneous sub-periods (right up, green and red lines) and applied corrections (right down) at station Szolnok (128600-99999), (plots extracted from the Climatol output).

The daily extreme values of hourly temperature were analysed using the 10th and 90th percentiles. Several extreme values were eliminated during the homogenization process (52 outliers), but the statistical properties of the percentiles computed from the two datasets (non-homogenized, homogenized) remained unchanged (Figure 7). The 90th percentile values were also computed for every station and interpolated on a regular grid (3000 m × 3000 m) by means of the Multiquadric spatial interpolation method. The spatial distribution of the 90th percentiles before and after homogenization is presented in Figure 8. The consistency of the homogeneous map when compared with the inhomogeneous one is evident in the southern and eastern part of the domain. The inhomogeneities were detected by the homogenization method and removed from the second map, hence the reliability of the 90th percentile spatial pattern was improved.

Figure 6 Standard deviations boxplots of the time series (all stations) before (quality-controlled) and after homogenization.

Figure 7 10th and 90th percentiles boxplots of the hourly temperature series (all stations) before (quality-controlled) and after homogenization.

Figure 8 Spatial distribution of the 90th percentile (°C) values computed from the hourly temperature series before (left) and after homogenization (right).

5 Discussion

The higher variability of daily series makes it more difficult to detect inhomogeneities in them because of a decreased signal-to-noise ratio, hence the advice of detecting the break-points on monthly aggregations of the original series (Szentimrey, 2011). Therefore, although it is expected that this problem is further increased in the case of sub-daily series, the same strategy can be applied to our hourly values. The drawback is that the detected break-points have only a monthly resolution. History of instrumental changes or station relocations can reveal more precise dates that would allow to adjust the break-points to improve the reconstruction of the homogenized series, but these details are often lacking in the metadata or difficult to obtain, and then the homogenized series may have small alterations in periods of several days, but they are not supposed to have a noticeable impact on their quality.

The statistical analysis of homogenization results of this study reveals that the hourly air temperature data retrieved from four standard measurement networks in Romania contain in-built inhomogeneities, requiring quality control and homogenization of the time series before using them for climate studies. The differences between before and after homogenization data series at station level may be important (e.g. the 90th percentile computed for HD-1 station is 25.7 °C before homogenizations, and 24.5 °C after homogenization) and they are well reflected in the spatial output (Figure 8), despite the small number of break points within the series.

The *Climatol* method has proved its efficiency for homogenization hourly data, and has delivered consistent results, such as homogeneous data series obtained from diverse meteorological networks, ready to use for climatological applications. It is worth mentioning that *Climatol* is based on clear and open procedure which covers all the necessary steps for obtaining reliable data series, i.e. break point detections are addressed, data correction is done, gaps filling is applied and homogenization is finally performed.

6 Conclusions

This study is the first endeavour which uses air temperature data at hourly resolution from four meteorological networks currently monitoring the territory of Romania. The results contribute to a better understanding of the climatic dependencies and the data base could be useful for different applications. While the National Meteorological Administration runs about 161 weather stations, this research has assimilated data and metadata from 354 stations, enhancing the homogenous coverage of the Romanian territory and its immediate vicinity. The resulting merged and homogenized dataset can serve as a basis for conducting different studies, e.g. the spatial-temporal variability of the air temperature diurnal cycle or freeze-thaw impact. At the same time, the output is the basis for constructing a national hourly gridded dataset at high spatial resolution (up to 1000 m × 1000 m), estimated to be ready within the next months.

The air temperature records used were obtained from four measurement networks: National Meteorological Administration (ANM), National Network for Monitoring Air Quality (RNMCA), Regional Basic Synoptic Network (RBSN), Meteorological Terminal Aviation Routine Weather Report network (METAR). Hourly temperature measurements were checked by applying four automated data quality control procedures: (1) climatological limits, (2) persistence, (3) temporal variation (step test), and (4) spatial consistency. The QC tests helped to identify and eliminate from the analysis the data with raw errors due to malfunctioning of the temperature sensors, or coding and transmission errors. The values of the corrected data set do not significantly deviate from the spatio-temporal variability of the air temperature specific to the latitudes of the study area.

The *Climatol* homogenization method was successfully employed for identification and correction of the suspicious values in the meteorological series analysed in this study. The monthly aggregates are used to detect the break-points on less variable series. Then hourly series are split by the break-points, and complete series are reconstructed from every homogeneous sub-period by means of the data infilling procedure implemented in the package. All the missing data were filled at this stage by considering the similarities between each station and the reference series, namely records from the nearest stations. The outputs were compared to the raw data (non-homogenized) revealing that the removal of the breakpoints, correction and homogenization, lead to a new data set, homogenous, with statistical properties very similar to raw data, but with trends and subsequent shifts very likely to reflect better the natural climate variability.

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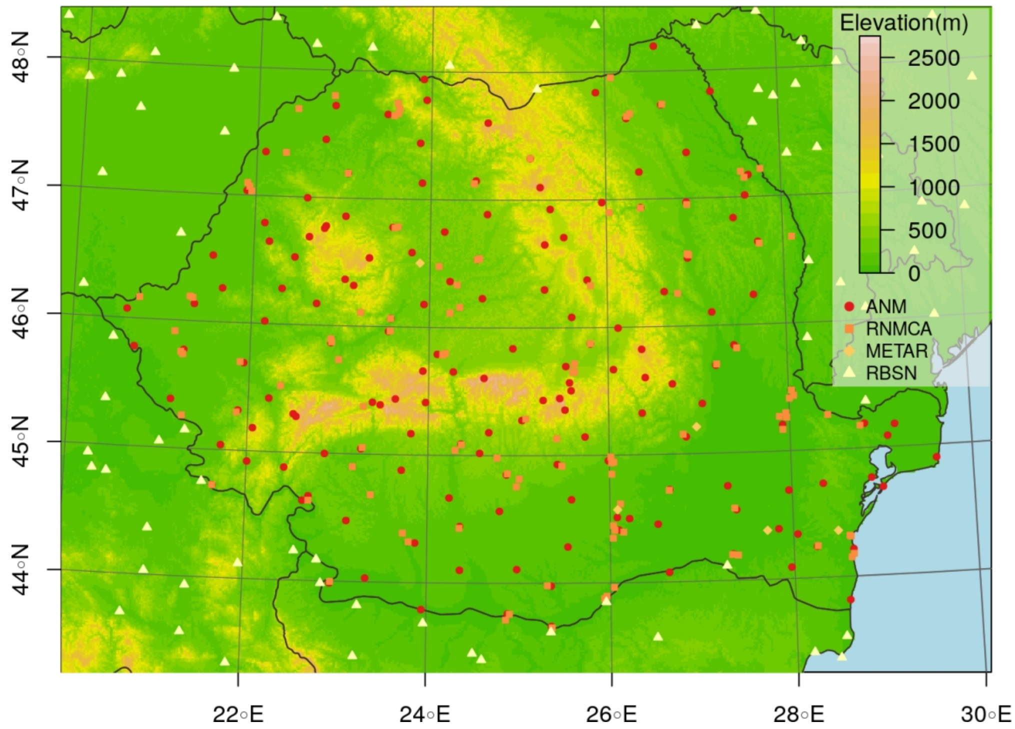

Figure 1: Spatial distribution of the selected weather stations (ANM, RBSN, METAR and RBSN).

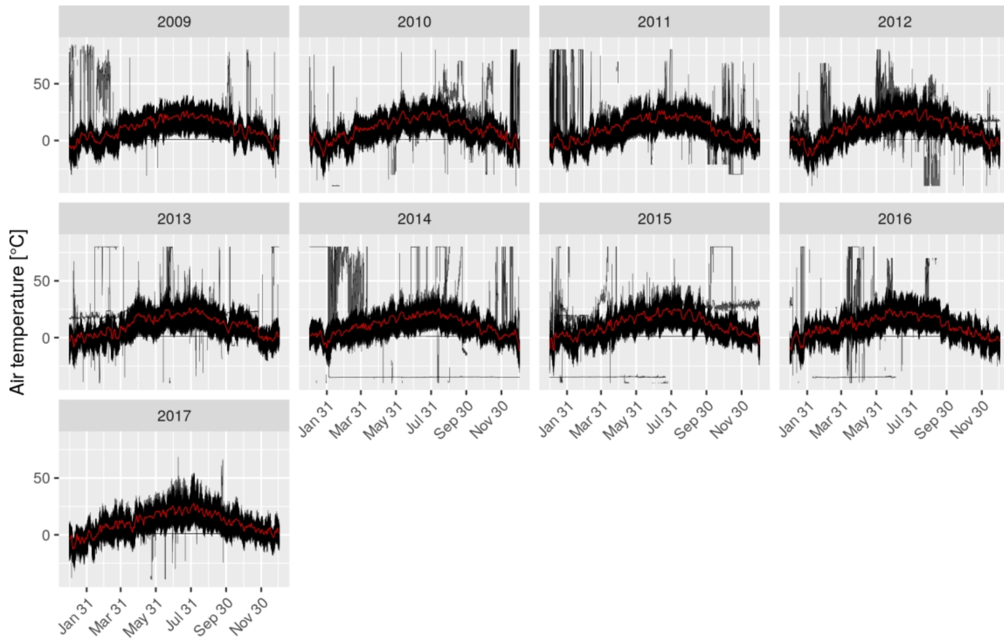

Figure 2: Hourly air temperature merged from four measurement networks (all stations). The spatial median across all stations is shown in red

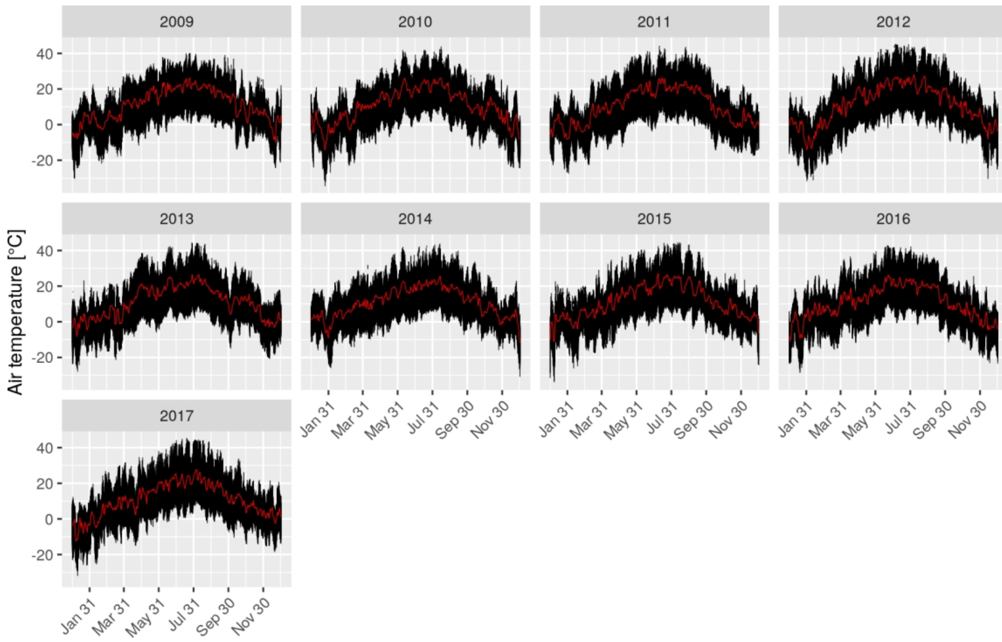

Figure 3: Quality-controlled and corrected hourly air temperature merged from four measurement networks (all stations). The spatial median across all stations is shown in red

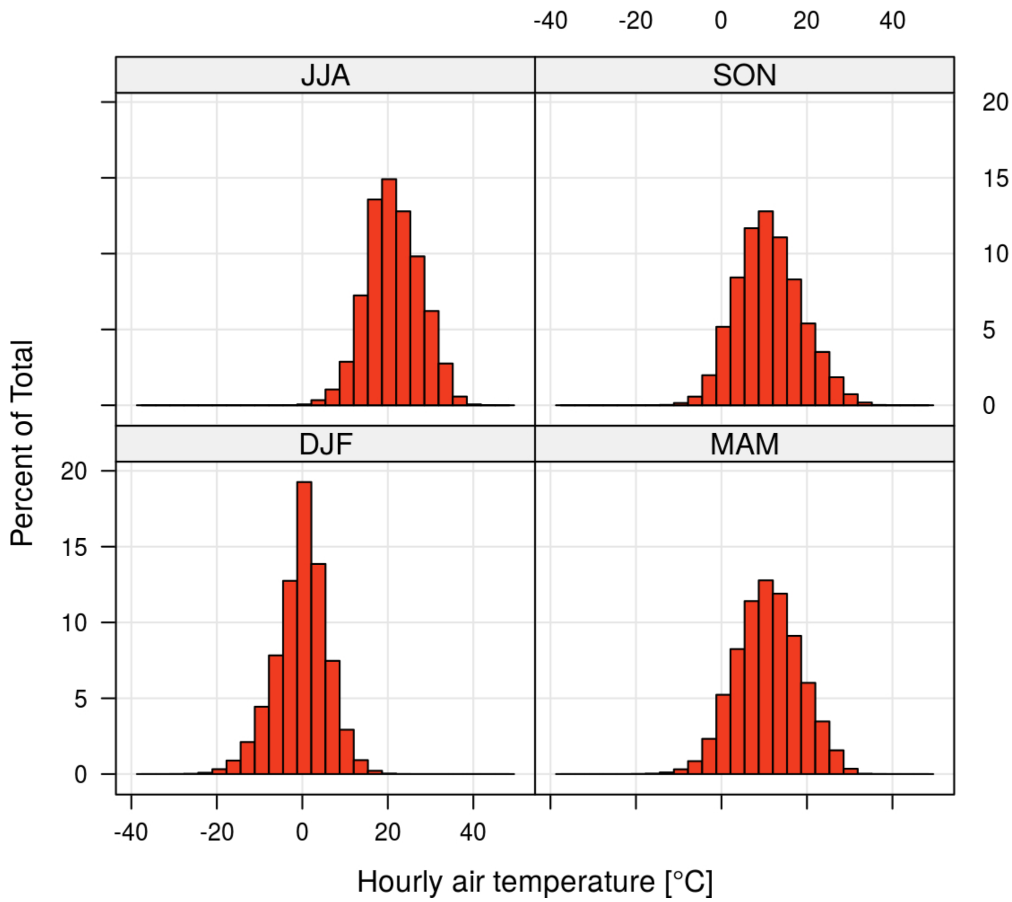

Figure 4: Seasonal histograms of the quality-controlled and corrected hourly air temperature merged from four measurement networks (all stations)

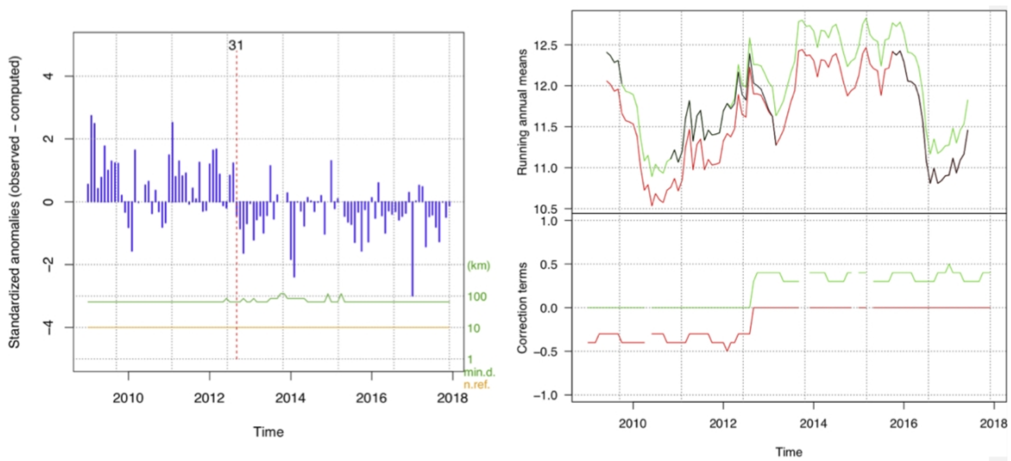

Figure 5: Example of break point detection (left) and the time series correction (right) at station Szolnok (128600-99999)

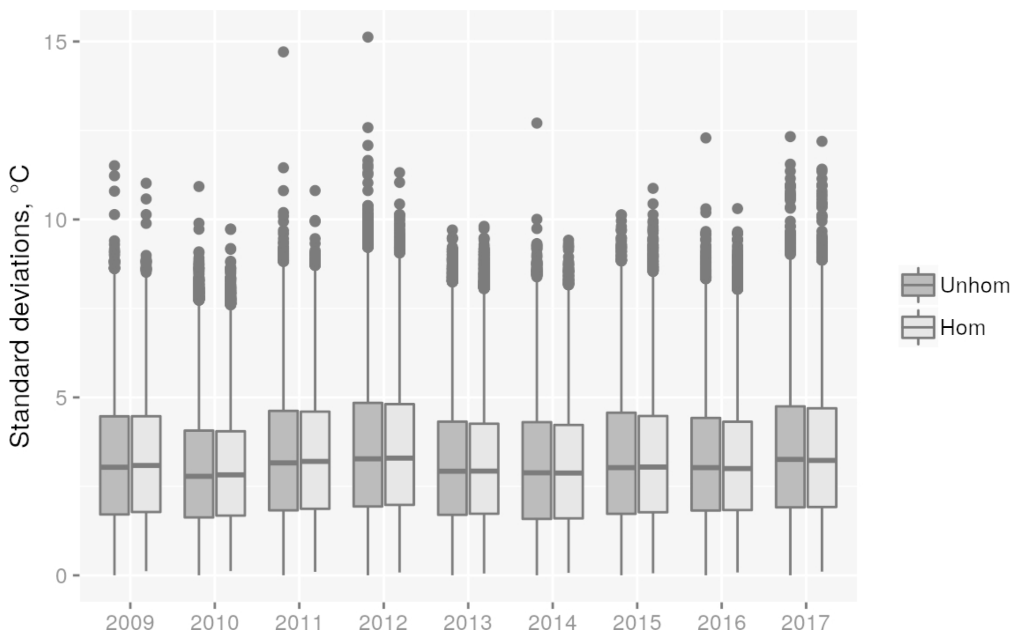

Figure 6: Standard deviations boxplots of the time series (all stations) before and after homogenization

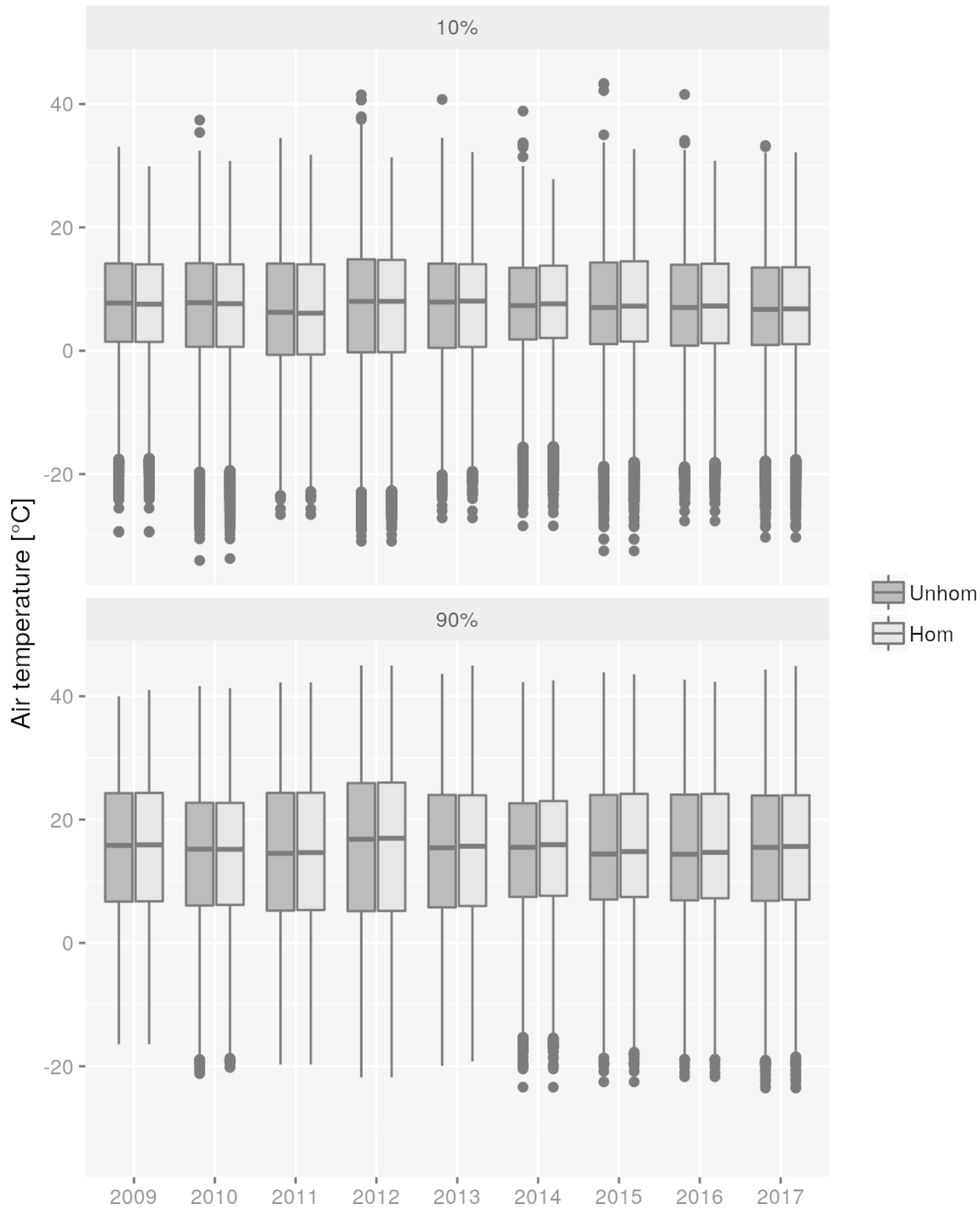

Figure 7:10th and 90th percentiles boxplots of the hourly temperature series (all stations) before and after homogenization

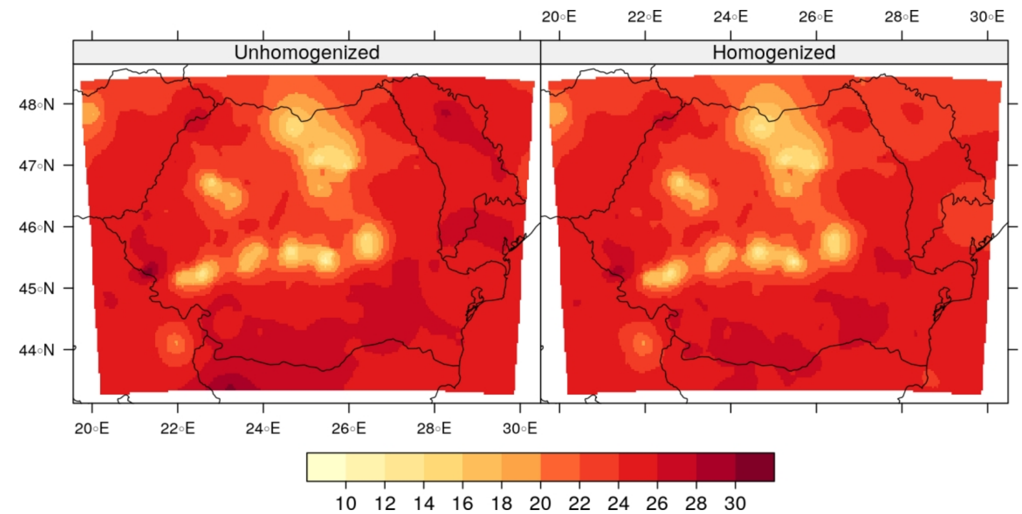

Figure 8: Spatial distribution of the 90th percentile (°C) values computed from the hourly temperature series before (left) and after homogenization (right)

Table 1. Availability (%) of the hourly air temperature data from the four networks used in this study

ANM	RNMCA	METAR	RBSN
92.1	73.5	78.1	37.0

Table 2. Number of break points detected within the four networks used in this study.

ANM	RNMCA	METAR	RBSN	Total
4	2	0	1	7