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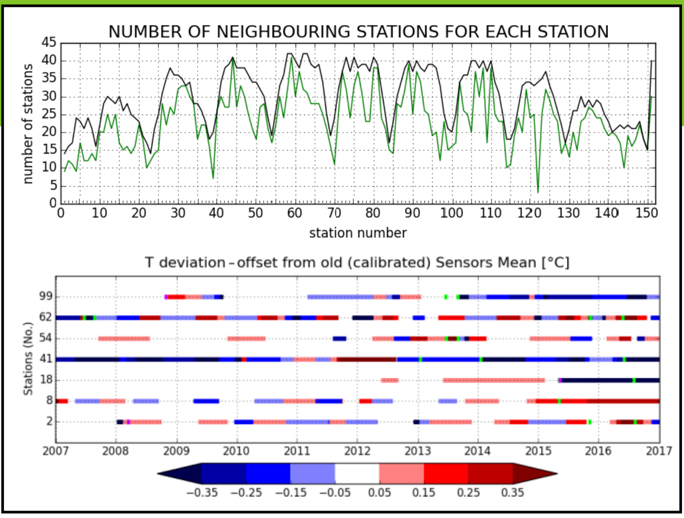

Analysis and Homogenization of WegenerNet Temperature and Humidity Data and Quality Evaluation for Climate Trend Studies

Simon Ebner

August 2017

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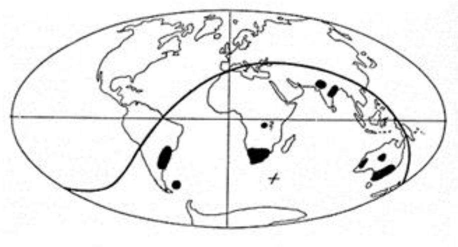

Alfred Wegener (1880–1930), after whom the Wegener Center is named, was founding holder of the University of Graz Geophysics Chair (1924–1930). In his work in the fields of geophysics, meteorology, and climatology he was a brilliant scientist and scholar, thinking and acting in an interdisciplinary way, far ahead of his time with this style. The way of his ground-breaking research on continental drift is a shining role model–his sketch on the relations of continents based on traces of an ice age about 300 million years ago (left) as basis for the Wegener Center Logo is thus a continuous encouragement to explore equally innovative ways:
paths emerge in that we walk them (Motto of the Wegener Center).

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Contact: Simon Ebner, MSc.
simon_ebner@gmx.net

Wegener Center for Climate and Global Change
University of Graz
Brandhofgasse 5
A-8010 Graz, Austria
www.wegcenter.at

Analysis and Homogenization of WegenerNet Temperature and Humidity Data and Quality Evaluation for Climate Trend Studies

Master Thesis

for the academic degree of
Master of Science
in Environmental System Sciences – Economics
at the University of Graz

Simon EBNER

Wegener Center for Climate and Global Change

Advisor:
Univ.-Prof. Mag. Dr.rer.nat. Gottfried Kirchengast

Co-advisor:
Dipl.-Ing. Jürgen Fuchsberger

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Abstract

The WegenerNet Feldbach Region climate station network is a pioneering long-term high-resolution climate research facility in the southeast of the state of Styria in Austria. It covers an area of about 22 x 16 km^2 and contains more than 150 measurement stations, which have been operating and providing meteorological data since the beginning of 2007.

In order to meet the WegenerNet's objective of building up long-term climate observations at a very high resolution, it is necessary to base them on homogeneous data time series. As a complete change of temperature and humidity sensors took place between 2013 and 2016, this Master thesis identifies possible inhomogeneities in the temperature and humidity data time series, especially due to the sensor changes.

By using inter-stational comparisons, the evaluation tries to detect unnatural change points. A cumulative sum approach is applied on daily temperature and humidity data, an approach already applied recently in 2015 to global scale annual temperature data time series. As a result, temperature and humidity correction values for deviating newly installed sensors are recommended if a detected unnatural change point matches the real date of the sensor change and if sensor uncertainty thresholds of $\pm 0.1\,°C$ (temperature) and ± 1.8 %RH (humidity) are exceeded by the discontinuity from the sensor change.

At about 13 % of all stations, small but significant temperature sensor-change inhomogeneities $>|0.1|\,°C$ were found. Likewise, significant humidity sensor-change inhomogeneities $>|1.8|$ %RH were found at about 7 % of all stations. These are corrected for in a new re-processing of the WegenerNet data.

Overall the evaluation, including stability checks for linear 10-year trends, confirms high and long-term stable data quality, in particular for temperature.

Zusammenfassung

Das Klimastationsnetz WegenerNet Feldbachregion ist ein langfristiges, hochauflösendes Pionierexperiment für die Klimaforschung in der Südoststeiermark in Österreich. Es erstreckt sich über eine Fläche von 22 x 16 km^2 und verfügt über mehr als 150 Messstationen, welche seit Beginn des Jahres 2007 in Betrieb sind und seither meteorologische Daten liefern.

Um die hohen Ansprüche des WegenerNet zu erfüllen, ist es notwendig für die zugehörige Klimaforschung homogene Datenzeitreihen zu verwenden. Da im Zeitraum zwischen 2013 und 2016 ein durchgehender Tausch der Temperatur- und Feuchtesensoren stattfand, beschäftigt sich diese Masterarbeit mit der Identifikation möglicher Inhomogenitäten in den Temperatur- und Feuchtedatenzeitreihen, speziell mit jenen, welche auf die Installation neuer Sensoren zurückzuführen sind.

Dazu wird eine Methode angewandt, die mit Hilfe von kumulierten Summen, basierend auf Tagesdaten von Temperatur und Feuchte, Wechselpunkte in den Zeitreihen sichtbar macht. Diese wurde bereits 2015 in anderem Kontext an globalen, jährlichen Temperaturdatenzeitreihen angewandt. Letztlich werden Korrekturwerte für die betroffenen neu installierten Sensoren vorgeschlagen, wenn ein gefundener Wechsel-Zeitpunkt mit dem wahren Datum des Sensortausches übereinstimmt und gleichzeitig die Unsicherheits-Bandbreite des Sensors $\pm 0.1\,°\mathrm{C}$ (Temperatur) und $\pm 1.8\,\%\mathrm{RH}$ (Feuchte) durch die Diskontinuität beim Wechsel überschritten wird.

Bei rund 13 % aller Stationen wurde eine kleine aber signifikante Inhomogenität bezüglich des Temperatursensor-Wechsels gefunden. Gleichermaßen wurde bei rund 7 % aller Stationen eine Inhomogenität wegen des Feuchtesensor-Wechsels entdeckt. Diese werden im Rahmen einer neuen Daten-reprozessierung korrigiert.

Zusammenfassend wird anhand von Stabilitätschecks (z.B. 10-Jahres-Trends) bestätigt, dass sowohl eine hohe als auch langfristig stabile Datenqualität sichergestellt ist, speziell für die Temperatur.

Acknowledgements

Firstly, I want to express my gratitude to my advisor Prof. Dr. Gottfried Kirchengast, director of the Wegener Center Graz, for giving me the opportunity to write this thesis at the Wegener Center for Climate and Global Change, especially for becoming part of the very interesting WegenerNet climate research project. Besides many hours of very fruitful discussions about the many different aspects of my work, he particularly taught me in scientific thinking and working.

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Last but not least I want to thank my parents, who made my studies and finally this thesis possible. Besides the financial support, I am very grateful for the continuous encouragement of going my way.

Contents

1. Introduction

The Summary for Policymakers of the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC, 2013) determines: *"Each of the last three decades has been successively warmer at the Earth's surface than any preceding decade since 1850. In the Northern Hemisphere, 1983–2012 was likely the warmest 30-year period of the last 1400 years (medium confidence)."* Moreover, the globally averaged combined land and ocean surface temperature has increased by 0.85 [0.65 to 1.06] °C[1], over the period 1880–2012. According to the APCC (2014) the Austrian mean temperature has increased by almost 2 °C in the same period. The increase since 1980 already amounts to about 1 °C.

This thesis deals with temperature and humidity data of the WegenerNet Climate Station Network Feldbach Region (FBR). It is a pioneering long-term high-resolution climate research facility in the southeast of Styria (federal state of Austria). It contains 154 weather stations within an area of about 22 x 16 km^2, i.e. one station per 2 km^2. The network provides data since the beginning of 2007, which makes it possible to observe weather data over more than a full decade now. The general idea behind the project is to build up long-term climate observations on a highly resolved regional to local scale for validating modern climate models and supporting other weather and climate research (Kirchengast et al., 2014, Kabas, 2012).

For the Styrian southeast, Kabas et al. (2011) found a significant trend of 0.45 [0.26 to 0.64] °C/decade[2] of annual-mean warming, over the period 1971–2007, by performing linear trend studies. To get correct results of such climate trend studies, it is necessary to work with homogeneous data. As the installed WegenerNet temperature and humidity sensors (TQ-sensors) were completely exchanged over the years 2013–2016, it became inevitable to check the homogeneity of the data over time, especially regarding to the compatibility of the different sensors. Cao and Yan (2012) state that inhomogeneities in climate time series are systematic differences, which are due to unnatural sources, like different measuring sensors in this case. Therefore, the aim of this thesis is to analyse the existing ten years of temperature and humidity data of the WegenerNet, to detect possible systematic change points (breakpoints) and finally to provide appropriate solutions for the homogenization of the data and the improvement of the data quality, as needed.

Chapter 2 gives on the one hand a short introduction of the structure and the idea of the WegenerNet project itself. On the other hand, the TQ-sensors used and the WegenerNet data processing are described. Finally, a short overview of the climate conditions and trends in the WegenerNet FBR are presented. To get an understanding of the weather and climate conditions in the focus region, Chapter 3 presents the annual cycles

[1] 90%-confidence-interval
[2] 95%-confidence-interval

of the regional mean temperature and humidity in the WegenerNet FBR. Furthermore, a short explanation of the necessity of homogeneous climate time series data is given.

To detect unnatural (technical) change points, Chapter 4 presents the homogenization method used in this thesis. It is based on an applied study of Cowtan (2015), who used a cumulative sum approach by Taylor (2000). It generally works by doing interstational comparisons, which is favourable due to the high density of available stations in the WegenerNet. Moreover, Chapter 4 describes how the recommended correction values (to correct systematic deviations) are calculated if found significant.

Finally, Chapter 5 depicts the found systematic change points and presents the recommended correction values. Beyond detected change points due to sensor changes and the corresponding homogenization application, also a location change of one station led to a systematic change point, and therefore to significant deviations of the data time series. Furthermore, Chapter 5 presents correction values for time ranges of failed processed data (e.g., times without installed sensor) based on an intrastational comparison of the affected time range. To verify the corrections found, two representative examples present the improvements of the data quality and the positive homogenization effects by applying the recommended corrections on annual temperature and humidity data in the context of checking the stability of linear 10-year trends.

Chapter 6 summarizes and concludes with the main findings.

For more detailed information, Appendix A presents in tabular form and with figures a summary of all treated station offsets and theoretic sensor deviations of temperature and humidity over the 10-year time range, a seasonal extension of the homogenization verification reported in the results chapter and some individual station local seasonality information.

2. The WegenerNet Climate Station Network

This chapter presents the most important facts about the WegenerNet Feldbach Region (FBR), also just called WegenerNet thereafter. It gives an introduction to the structure of the climate station network and its idea behind. Furthermore, there is a presentation of the used sensors, the data processing system and also a short overview of the weather and climate (change) in the WegenerNet Feldbach Region (FBR). Since this Master thesis focuses on the analysis of temperature and relative humidity data, this chapter concentrates on these meteorological parameters. A more detailed description of the WegenerNet can be found in Kirchengast et al. (2014) and Kabas (2012).

2.1. WegenerNet Feldbach Region (FBR) Overview

The WegenerNet climate station network in the FBR is a pioneering weather and climate experiment at a very high resolution. It is located in the hilly southeast of Austria, around the Styrian city of Feldbach. Figure 2.1 illustrates its location within the north-eastern region of the Greater Alpine Region within the Histalp station network (ZAMG, 2017)[1]. This region is referred to as the WegenerNet FBR, or just WegenerNet, in this thesis.

There exists another smaller WegenerNet climate station network in the Johnsbachtal area, which is also operated by the Wegener Center. Due to its alpine location in the north of Styria (Ennstal/Nationalpark Gesäuse), this WegenerNet Johnsbachtal (JBT) network represents an alpine complementary network to the FBR network. In contrast to the WegenerNet FBR, the eleven stations in the Johnsbachtal are located in much higher altitudes beginning at around 700 m going up to 2100 m (Wegener Center, 2017d). We do not further adress this more recently established WegenerNet JBT network in this thesis.

The WegenerNet project started in spring 2005 with the idea of a very dense weather station network with the aim of being able to validate high-resolution regional climate models. At the newly founded Wegener Center for Climate and Global Change this idea was realized with starting regular measurements at the beginning of 2007. After a pilot phase from 2007 to 2010 the system is fully operational and data is available not only for researchers and other professionals but also for schools and weather enthusiasts.

The WegenerNet FBR incorporates 154 climate stations within an area of around 22 x 16 km^2. Stations 152 and 153 are external stations, in which station 152 only mea-

[1]The Histalp station network is set up for evaluating climate change in the Greater Alpine Region.

Table 2.1.: Overview of the different WegenerNet station types and measured parameters. The + sign indicates an additional measured parameter to the base station type stations (adapted from Wegener Center (2017b)).

Station type	**Measurement** Parameters	**Station ID**
Base station (129 stations)	temperature, humidity, precipitation	All stations except other types
Special base station (12 stations)	+ soil temperature, pF-value	6, 15, 19, 27, 34, 50, 54, 78, 84, 85, 99
	precipitation only	152
	temperature, precipitation	153
Primary station (11 stations)	+ solid precipitation, wind parameters	11, 32, 37, 44, 72, 74, 82, 101, 132, 135, 139
Reference station (1 stations)	+ solid precipitation, wind parameters, air pressure, net radiation	77

sures precipitation and station 153 temperature and precipitation. Station 154 is recently (2017) established as an additional station at the "Kapfensteiner Kogel". Therefore, for the following analyses just the 151 internal WegenerNet FBR stations with long data recors since 2007 are used. The grid density of these stations is about 1.4 x 1.4 km^2 per station, which characterizes the WegenerNet as the first long-term climate station grid at this scale. Figure 2.1 gives an overview of the different station types. The 151 stations are equipped with different amounts of sensors. The stations are named according to their meteorological parameters they measure by the different sensors. Most of them are “base stations” which provide data for temperature, humidity and precipitation.

Table 2.1 gives a detailed overview of the provided meteorological parameters for all station types. For the following analysis it is important to mention that both – temperature and humidity – data parameters are available over all 151 stations. The stations are located in a moderate altitude ranging from 260 m to 520 m. They are further sorted by different location classes (see Table 2.2).

2.2. Temperature and Humidity Sensors

To reach the best possible data quality, for the temperature data generation a PT1000 based sensor is used, which is produced by the company GeoPrecision GmbH[2]. Measurements are based on the temperature-dependent resistance of platinum. This sensor provides a very high accuracy of ±0.05 °C if it is calibrated to the data logger used for collecting the data, and ±0.1 °C if it is not.

[2] www.geoprecision.com

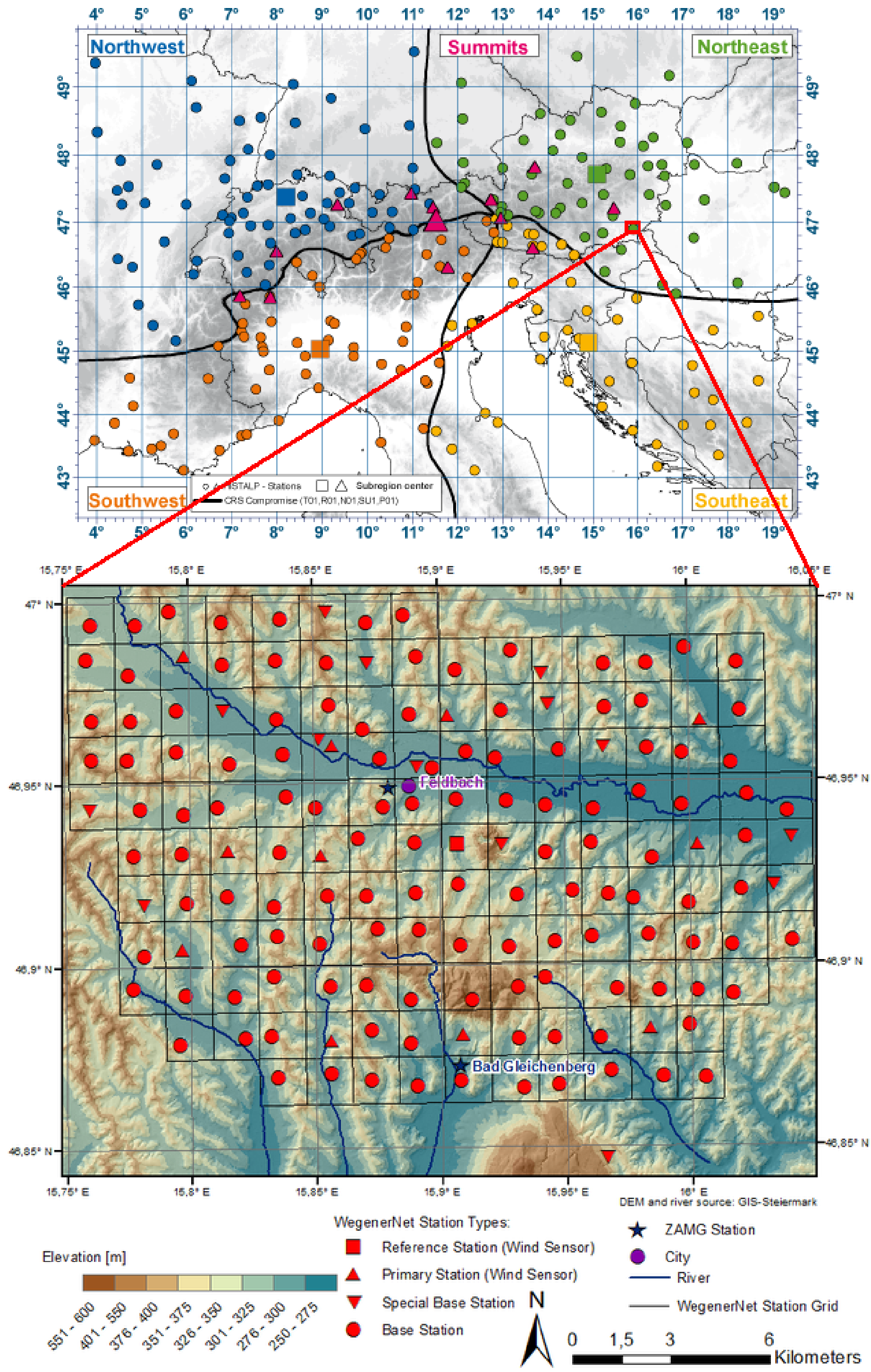


Figure 2.1.: WegenerNet FBR (bottom) with arrangement of WegenerNet stations (Wegener Center, 2017c) within the eastern part of the Greater Alpine Region (top), illustrated as part of the Historical instrumental climatological surface time series network of the Greater Alpine Region (Histalp) (ZAMG, 2017).

Table 2.2.: Location classes of WegenerNet stations.

Location class
Valley
Base of slope
Lower slope
Middle slope
Upper slope
Hilltop

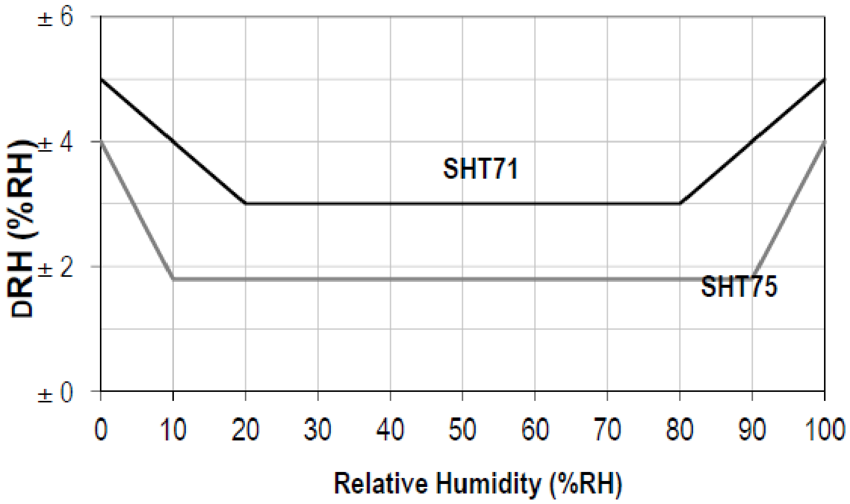


Figure 2.2.: Accuracy (maximal RH-tolerance) of relative humidity sensor tested at 25 °C (Sensirion AG, 2016).

Relative humidity data is generated in the WegenerNet by a sensor called SHT75. It is produced by the company Sensirion AG[3]. The sensor is able to measure temperature and relative humidity (RH) via two calibrated micro-sensors, which only RH measurement is used. The accuracy of the humidity sensor is ±1.8 %RH between 10 %RH and 90 %RH, tested at 25 °C. Below and above these values accuracy rises up to 4 %RH at 0 %RH and 100 %RH. Figure 2.2 shows the exact tolerances of the relative humidity and temperature measurement.

Figure 2.3 shows an example of an used temperature and humidity sensor (TQ)-sensor. At the top of the device both sensors (PT1000 and SHT75) are installed.

[3] www.sensirion.com

Figure 2.3.: Example of a temperature/humidity (TQ)-sensor with installed PT1000 and SHT75 sensors.

2.3. WegenerNet Processing System (WPS)

The WegenerNet Processing System (WPS) is defined as the complete data generation process in the network. It contains four main stages: The first three stages are located in the core processing system, and the fourth stage represents the connection between data generation and data utilization. It is called Visualization and Information System (VIS) and provides the generated data in a handsome way at the WegenerNet data portal (Wegener Center, 2017a). As this fourth step is negligible in this context, it will not be mentioned further in the following description of the processing system. For more details about the WPS, see Kabas (2012), Kirchengast et al. (2014) and Scheidl (2014).

The three essential data processing stages are defined as processing levels.

- First level (level-0-processing): The WPS starts with the Command Receive Archiving System (CRAS). This system controls the data transmission from the climate stations to the data server and further the transmission to the database. Temperature and humidity data are measured every five minutes at each station. For the transmission, different values are merged to data packages. Over the whole WegenerNet FBR one complete transfer cycle lasts for 30 minutes and is repeated every hour. Then the data is separated by parameters and climate station and finally stored as Level-0 data in the database.

- Second level (level-1-processing): After every finished transfer cycle, the data values are proved for their plausibility. This Level-1-processing is done by the Quality Control System (QCS). This system is built up in seven steps. Every step does some parameter-specific monitoring. On the one hand, the QCS checks if the Level-

Table 2.3.: Structure of the different quality control layers of the QCS with corresponding quality control flag (QC-Flag) (Kabas, 2012, p. 81).

Layer ID	QC-Layer	QC-Flag
0	check if station in operation	-
1	test of data availability	2
2	test of technical sensor-specific plausibility	4
3	test of climatological plausibility	8
4	test of temporal variability	16
5	test of intra-station-consistency	32
6	test of inter-station-consistency	64
7	test against external references	128

0 data are climatologically plausible. Then the values are controlled temporally by looking for obtrusive jumps or value stagnations. Furthermore, the QCS checks the values for different climatological plausible limits. On the other hand, the data is proved by some sensor-specific algorithms and comparisons with neighbouring stations. At the end, the QCS flags every data value with a Quality Control Flag (QC-Flag). The flag value depends on the outcome of the QCS. The concrete layers of the QCS checks are shown in Table 2.3.

- Third level (level-2-processing): Finally, the WPS Level-2-processing is done by the Data Product Generator (DPG). It uses only data with highest quality from Level-1-processing. Out of these data values products are generated for example for interpolated grid data. Furthermore, 5-min data values are aggregated to other formats like, e.g., hourly, daily or annual data. The DPG further closes data leaks by interpolation of the station data. Depending on the degree of necessary interpolation, values are flagged by a Data Product Flag (DP-Flag) value. Table 2.4 shows the five possible DP-Flag values (zero to four) and the corresponding properties of the interpolations. As the DPG aggregates 5-min data to larger timescale products, a mixture of different DP-Flags result in a mean value for the Quality Flag (Q-Flag) over all individual DP-Flag values.

2.4. Weather and Climate in the WegenerNet FBR

The WegenerNet Feldbach Region, just called WegenerNet thereafter, is located in the southeast of the Styrian federal state of Austria. More exactly it stretches about $22 \times 16\,\mathrm{km}^2$ around the city of Feldbach. This chapter will give a short overview of the climatological conditions in the region.

The WegenerNet lies in the middle of the southeast alpine foothills, which includes the hilly Styrian southeast and the southern Burgenland, which is illustrated in Figure

Table 2.4.: Quality Flag values of Level-2 data and corresponding properties (adapted from Kabas, 2012, p. 100).

Q-Flag	Property of parameter value
0	Measured value at station
1	Interpolated in station time series (temporal)
2	Interpolated from surrounding stations (spatial)
3	Interpolated from gridded data
4	Error value (no interpolation possible due to lack of data)

2.4. The WegenerNet is assigned partly to the east-styrian foreland and partly to the valley floors of the foothills (Kabas (2012), adapted from Lieb (1991)).

The Raab valley (marked in green in Figure 2.4) crosses the WegenerNet from north-west to east-southeast and therefore divides the research area into a northern and a southern part, which is also shown in Figure 2.1. Both are part of the southeast hill land. The characteristics of this landscape are the so called "Riedel" which can be described as the typical hills of the southeast alpine foothills. The highest "Riedel" in the WegenerNet is the Gleichenberger Kogel which has a maximum height of 598 m. The lowest altitude of around 250 m can be found in the east, where the Raab leaves the WegenerNet.

The weather and climate in the focus region of course also depends on large-scale and global-scale weather conditions and events. Especially the Alpine mountain ridges play an important role, as they function as a big barrier for advective air. One special and globally very important event which has effects on the regional weather and climate is the El-Niño-Southern Oscillation (ENSO). For more details concerning further big influence factors to the regional climate have a look at Kabas (2012) and for the ENSO see Kappas (2009).

On a regional scale, weather and climate in the focus region is – referred to Wakonigg (1978) – strongly dependent on the terrain and location (see location classes in the WegenerNet in Table 2.2).

On the one hand, the climate in the valleys is characterized by typical continental conditions. The effects are relatively cold winters and warm summers. Cold winters in valley locations arise by the tendency for inversions, especially during the winter half year. Hardly no outflow possibility of cold ground air causes that effect. Especially if there is no air mixing by larger wind and flow systems, inversions and fogging is likely.

On the other hand, higher located places are thermally balanced because of better mixed air. In concrete, it depends strongly on the altitude of the upper limit of the fog in respect to the upper limit of the inversion. Comprehensively, continental climate conditions are softened in higher places. Sunshine duration is higher in winters, which causes relatively warmer winters compared to the low altitude valleys[4]. Due to the more exposed locations, these places are more vulnerable to heavy storm, hail or convective

[4] An evaluation of that effect will be presented in Section 5.1.4

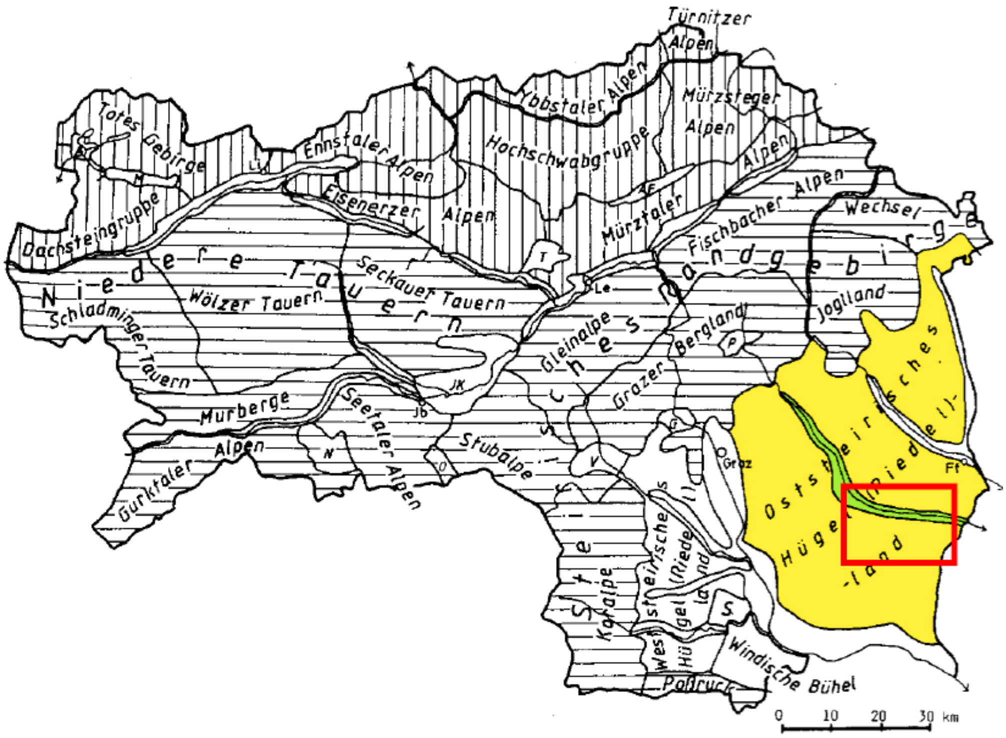


Figure 2.4.: Geographic structure of Styria with the yellow marked east-styrian foreland, the green marked valley of the Raab river and the red marked WegenerNet FBR (Kabas (2012), p. 7, adapted from Lieb (1991))

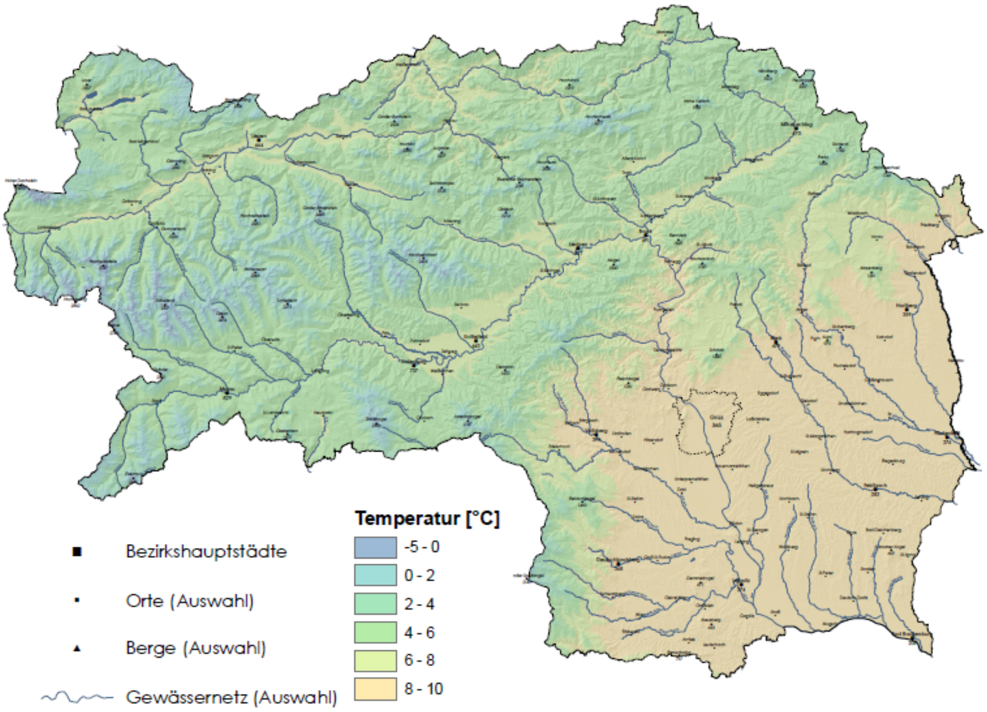


Figure 2.5.: Annual mean temperature in °C (1971–2000 averages) over Styria; adapted from Prettenthaler et al. (2010).

rainfall events (Wakonigg, 1978).

Figure 2.5 shows the mean annual temperature for Styria. The WegenerNet is located in the southeast and therefore in the mildest part of the Austrian federal state. The annual mean temperature is about +10 °C, which is treated in more detail in the next Chapter 3.

Figure 2.6 presents the mean annual precipitation amount in Styria. Precipitation amounts are much higher in the mountainous northwest of the federal state. That is caused on the one hand by the higher altitude (especially at high mountains), and on the other by the influence of northern weather conditions (advective rainfall events with atlantic origin). The south-eastern region has up to three times lower precipitation amounts compared to the maxima in the northwest, which is mainly caused by the screening effect of the Alps during northern weather conditions. The WegenerNet is located in the relatively dry southeast of Styria. Biggest rainfall events in the focus region are due to Adriatic cyclone events and heavy convective thundershowers in summer. For a closer look at precipitation in the WegenerNet and the corresponding measurement system, see Szeberenyi (2014).

As the WegenerNet research focus is on observing climate change in the region and Figures 2.5 and 2.6 just present climatological mean information for the period 1971–2000, it is important to have a closer look on climate trends. Using linear trends, global

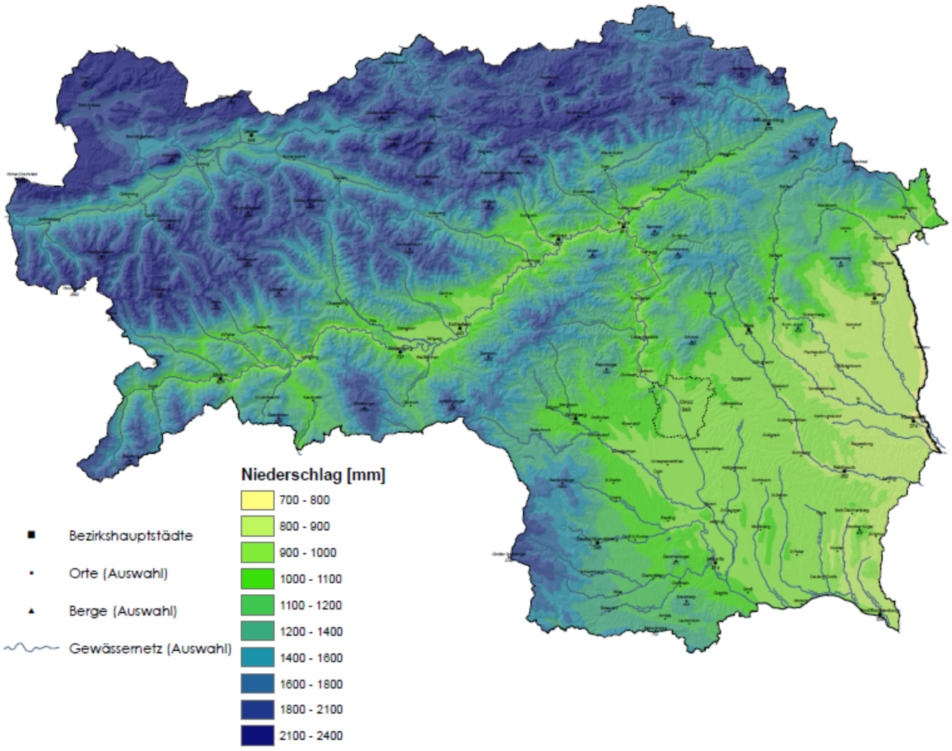


Figure 2.6.: Mean annual precipitation amounts (1971–2000 average) over Styria, given in mm; adapted from Prettenthaler et al. (2010).

mean temperature has increased by 0.85 [0.65 to 1.06] °C[5] over the period 1880 to 2012 (IPCC, 2013). Furthermore, in Austria the mean temperature has increased almost by 2 °C in the same period, which means that temperature increase is about a factor of two higher in Austria compared to the global trend. Mainly responsible for the different strength of the trend are the last few decades. Since 1980 the Austrian mean temperature has increased approximately by 1 °C, in contrast to about 0.5 °C globally (APCC, 2014).

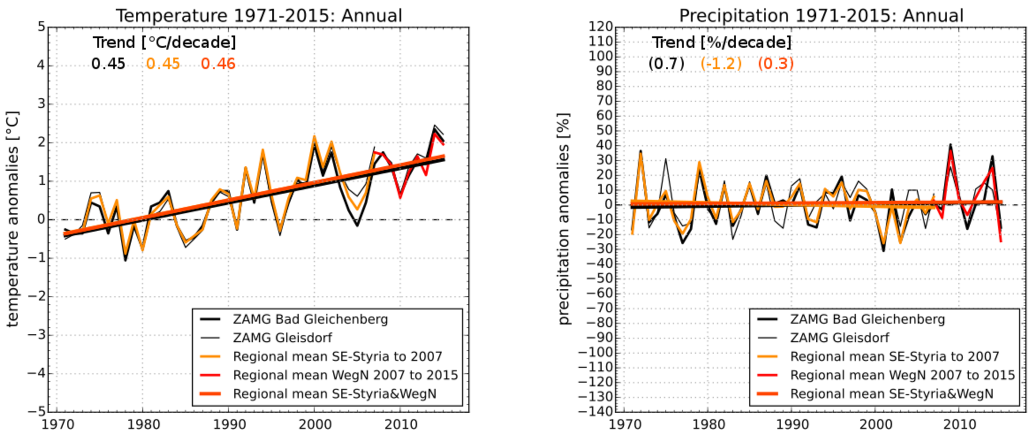
For the Austrian annual precipitation amount there cannot be found any significant trend, which is due to regional differences. On the one hand, there can be found a positive trend in western Austria, on the other hand, precipitation amounts in the southeast of Austria are decreasing over the last 150 years. Both trends are similar in their magnitude by about 10–15 %. Furthermore, there can be found a likely trend of increased winter and decreased summer precipitation amounts (APCC, 2014).

For a closer look at the Austrian's southeast climate development over the last decades, Figure 2.7 illustrates annual data for temperature and precipitation anomalies from 1971 to 2015 based on an internal evaluation by Kabas et al. (2016). The calculations are an extension of the work by Kabas et al. (2011). In this more recent work regional mean temperature for the southeast of Styria for 1971–2007 are linked with newest data from the WegenerNet until 2015 and with ZAMG data. Trends are shown for the regional mean of the Styrian southeast (1971–2007), for the WegenerNet regional mean (2007–2015), and a combined trend out of these data sets. Furthermore, the data of two ZAMG stations of Bad Gleichenberg and Gleisdorf are plotted to check the analysis against external comparative time series.

Kabas et al. (2016) show significant increasing temperature trends over all different considered time ranges. Observing the time range 1971–2007, regional mean temperature increased by 0.45 [0.26 to 0.64] °C[6] per decade. The high magnitude of the trend can be explained by a relatively cold period from the early 1970s to the middle of the 1980s. Moreover, the period since the beginning of the 1990s is characterized as a warmer period. Consequently, the mentioned observed trend is higher compared to longer-time-ranged analyses. Precipitation in Figure 2.7(b) shows no significant trend.

Figure 2.8 presents seasonal observations from Kabas et al. (2016). For the summer season there was found the largest significant temperature trend in magnitude by 0.71 °C per decade for the period 1971–2007, which is in accordance to the APCC (2014). Temperature trends for the winter season show much lower trend slopes and the 1971–2007-period-trends are even not significant. Seasonal precipitation shows no trend for winter. In summer there is an insignificant tendency to lower precipitation amounts, which would be again in accordance to the argumentation of the APCC (2014).

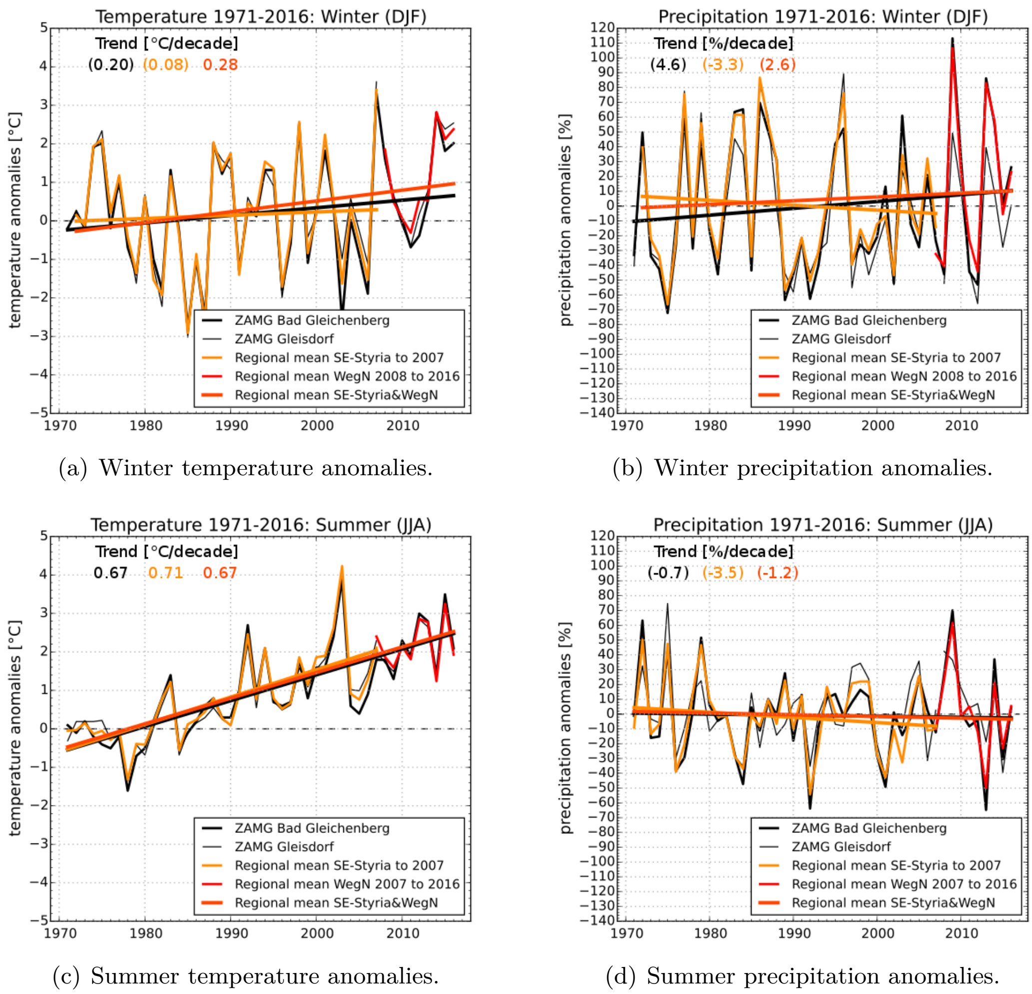
[5]The values in brackets stand for the 90 %-confidence-interval.
[6]The values in brackets stand for the 95 %-confidence-interval.



(a) Annual temperature anomalies.

(b) Annual precipitation amounts anomalies.

Figure 2.7.: Annual temperature and precipitation anomalies (compared to period 1971–1990) and corresponding linear trends with slopes. Significant trends (95 %-confidence-interval) are marked without brackets (Kabas et al., 2016).



(a) Winter temperature anomalies.

(b) Winter precipitation anomalies.

(c) Summer temperature anomalies.

(d) Summer precipitation anomalies.

Figure 2.8.: Summer and winter temperature and precipitation anomalies (compared to period 1971–1990) and corresponding linear trends with slopes. Significant trends (95 %-confidence-interval) are marked without brackets (Kabas et al., 2016).

3. Temperature and Humidity in the WegenerNet

Chapter 2.4 treated with climatological mean values for the WegenerNet and corresponding changes over decades. The first part of this chapter concentrates on seasonal variabilities within years. It emphasizes the meteorological parameters temperature and relative humidity because these are subject of the ongoing data homogenization work analysis in Chapter 4. The second part of the chapter focuses on possible inhomogeneities in the time series and the likely reasons for them.

3.1. Annual cycle of temperature and humidity

As depicted in Figure 3.1, temperature is fluctuating with seasons relatively constant. The black curve indicates each day's regional mean value. The red curve depicts a smoothed version, which is done by the help of a gaussian filter with a filter width of 30 days. Overall, it can be summed up that temperature oscillates relatively constant around the annual mean temperature of about +10 °C (see Section 2.4).

Figure 3.1 shows that, on average, temperature reaches its peak in July. The smoothed peak magnitude of the daily mean temperature lies around 20 °C. The daily regional mean shows values around and over 25 °C for some days. In contrast, lowest temperatures are measured around the turn of the year, where the regional mean value lies around 0 °C on average. Single days reach daily mean temperature of around –10 °C or lower at the end of December, respectively at the beginning of January. One special eye-catching phenomenon are the very warm last three winters (2014–2016), which can be easily distinguished from former winters without any calculation.

Figure 3.2 shows the daily regional mean curve for the relative humidity. Due to much higher variability, caused by different weather conditions, humidity displays a much more unstructered seasonal development. Nevertheless, with the help of the drawn smoothed red curve a more or less constant pattern can be found. Relative humidity reaches its peak at the end of the year at around 90 %RH daily mean on average. Some days reach daily mean maximum values near to 100 %RH, especially in the last few years, which is possibly due to the new installed humidity sensors in the field and the therefore better data quality. More information on that fact is presented later on in Section 4.6. Relative humidity quickly decreases during the first few months of the year. Beyond the minimum turning points (on average at the beginning of spring) the values are slowly increasing again towards its maximum at the end of the year.

Furthermore, the relative humidity regional mean shows an interesting decrease especially in autumns and winters until 2013. From then on, the regional mean again reaches

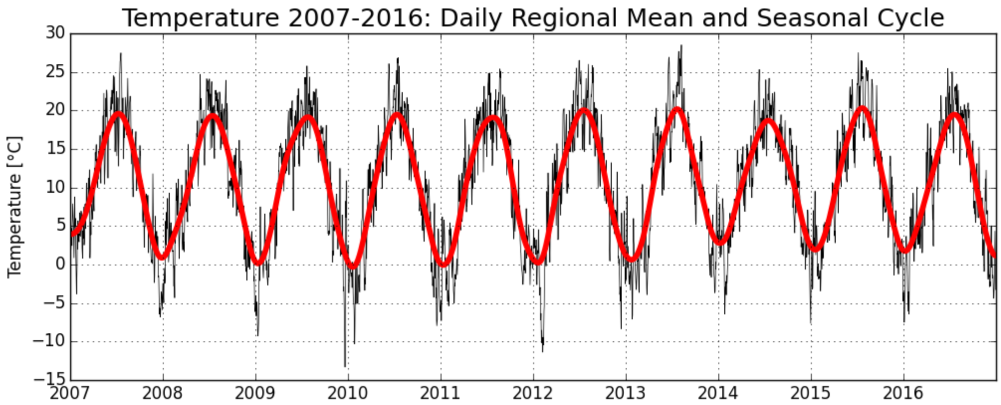


Figure 3.1.: WegenerNet daily regional mean temperature (black curve) in °C and a gaussian-filtered smoothed seasonal-cycle curve (red).

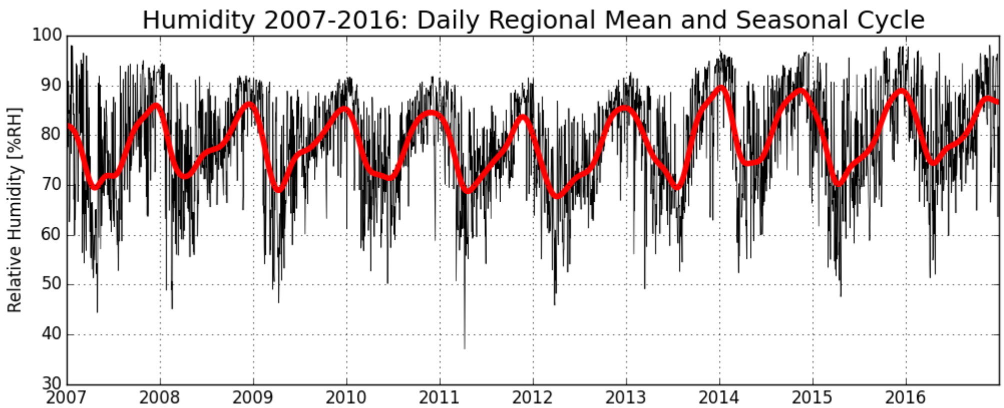


Figure 3.2.: WegenerNet daily regional mean relative humidity (black curve) in %RH and a gaussian-filtered smoothed seasonal-cycle curve (red).

higher peaks in autumns and winters (similar to 2007 or 2008), which is due to better data quality caused by the new installed sensors (beginning of changes in summer 2013). This phenomenon will be treated in more detail in Section 5.2.

3.2. Inhomogeneities in Data Time Series

"The inhomogeneity in climate time series is the systematic differences that cannot be ignored relative to the natural variability and are caused by unnatural sources. A homogeneous climate time series is that where the variations are caused only by variations in weather and climate. The non-homogeneity of time series can be a gradual trend and can also be a sudden discontinuity (breakpoint)." (Cao and Yan (2012) p. 60) This quote describes very well what inhomogeneities in climate data time series are and why it is necessary to remove them as good as possible.

For building up correct climate trend studies it is necessary to base them on homogeneous data time series. As the WegenerNet is born for evaluating long term climate trends on a regional scale, data homogenization is inevitable. This thesis is focussed on the detection of sudden discontinuities (breakpoints, respectively change points) due to sensor changes in the WegenerNet station network. After ten years of climate observation, all TQ-sensors were already replaced at least once. The dates of the changes are well documented, which makes it possible to overlap them with the results of a change-point-detection. Caused by the different tolerances, and of course possible damaged sensors, inhomogeneities in the time series are likely to a certain extend. Furthermore, detected change points may also arise by location changes of a station, which are of course well documented by date, too. How the used change-point-detection method looks like is explained in the following Chapter 4.

4. Homogenization Method

Inhomogeneities in data time series may arise by a lot of sources (Cowtan, 2015). As temperature and relative humidity are depending on many different parameters – which are often correlated with local weather conditions and features of the landscape – it is of course impossible to homogenize temperature data by direct comparisons between stations. In contrast, it is necessary to detect real changes in station behaviour and therefore to distinguish them from local station noise in the time series. As this Master thesis focuses on possible changes in stations data behaviour due to sensor changes especially, it is required to detect changes which are caused by installing new sensors. The aim is to obtain homogenized time series along the 10+ years of WegenerNet data for applying them in different trend studies which have the claim of reflecting the real-world changes as Cowtan (2015) calls them.

The used method for detecting change points is based on a method of Cowtan (2015). He uses the method on the temperature data from the so-called Global Historical Climatology Network (GHCN). This Master thesis applies the method as well to temperature data as to relative humidity data, which is overall possible due to the fact of existing continuous time series data for both parameters, temperature and relative humidity[1]. For the concrete change point detection, Cowtan (2015) uses an approach by Taylor (2000), who uses cumulative sums of data time series for detecting changes. There will be a more detailed description of the constitution and usefulness of cumulative sums in the further course of this chapter.

For applying the method, a pool of potential reference neighbouring stations for each station is necessary. The great advantage of the WegenerNet lies in its dense network structure. That fact allows to apply relatively stringent criteria for limiting down the pool of potential agreeing neighbouring stations (PNBS) to agreeing neighbouring stations (ANBS). That stringent criteria guarantee optimum reference values. The concrete selection of neighbouring stations is described in detail in the overnext Section 4.2.

4.1. Datasets Used

In general, the analysis is executed by using daily mean data exclusively. So, there exists one value for each day and parameter, which is a computed average out of all 5-min base data values per day, which is already explained in Section 2.3.

In concrete, all the calculations are based on WegenerNet level-2 station data at QCS-version 4 and DPG-version 6.[2] During working out this thesis one very important data

[1] In contrast to non-continuous time series like precipitation data. A corresponding test-evaluation was tried and is briefly reported on in Section 5.4.

[2] See Section 2.3 for WegenerNet Processing System (WPS)

Table 4.1.: Temperature data quality.

Q-Flag	Proportion of daily data [%]
0	98.45%
1	0.16%
2	1.39%
3	0.00%
4	0.00%

Table 4.2.: Relative humidity data quality.

Q-Flag	Proportion of daily data [%]
0	56.24%
1	14.86%
2	28.89%
3	0.01%
4	0.00%

processing weakness was detected. By using DPG-version 4 in the first stadium of the work, some unrealistic data outliers were found. The reason was some positive weighting of Q-Flag-0 data compared to higher flagged values. This led to distorted values as well in the temperature data as in the humidity data. Furthermore, seasonal and annual data were affected too. After that, the data were re-processed (update from DPG-version 4 to 5), which provided much better results. By the last update from DPG-version 5 to 6, another QCS-version (4) was implemented as reported by Scheidl et al. (2017), which significantly improved especially the humidity data.

The time range of the analysis covers the full ten years from January 2007 to December 2016.

Tables 4.1 and 4.2 depict the overall data quality of daily temperature and humidity data. They verify the much lower data quality of the humidity data compared to the temperature data. As Table 4.2 shows, overall only 56.2 % of the daily humidity data provide Q-Flag-0 data. The worst humidity data is provided between 2010 and 2014 (especially in autumns and winters), which is caused by the continually decreasing data quality and was finally stopped by the beginning of TQ-sensor changes in summer 2013. The concrete temporal distribution of Q-Flag-0 data is shown later on in Figure 4.2.

4.2. Selection of Neighbouring Stations

To get reference data values for each station's data, other (neighbouring) stations are used for providing them. Due to the fact of the high density of the WegenerNet, it is possible to select at first so called potential agreeing neighbouring stations (PNBS) which are in the direct surroundings of the candidate station.[3] For the temperature analysis a radius of 5 km is chosen. So, all stations which are inside of these circled area are defined as PNBS. For the humidity analysis all available stations represent the pool of PNBS (see Subsection 4.2.2).

In the next step, so called agreeing neighbouring stations (ANBS) are picked out of all PNBS by special algorithms. For this latter purpose, a comparison between every possible pair of stations is carried out.

4.2.1. Temperature

For the temperature analysis, PNBS get the status of an ANBS if the standard deviation of the difference between a PNBS and the candidate station is at most 10 % of the standard deviation of the candidate station's data values itself. If a PNBS gets the status of an ANBS, it fulfills the 10 %-accordance-criterion. That is the case if the following inequality holds:

$$\sqrt{\frac{1}{n} \cdot \sum_{i=1}^{n} [(p_i - c_i) - (\bar{p} - \bar{c})]^2} < 0.1 \cdot \sqrt{\frac{1}{n} \cdot \sum_{i=1}^{n} (c_i - \bar{c})^2} \tag{4.1}$$

with:
p ... daily data of the PNBS
c ... daily data of the candidate station
i ... day
n ... number of days

The standard deviation of the candidate station (right side of equation 4.1) is of course largely reasoned by seasonal fluctuations. Therefore, the accordance-criterion percentage can be set relatively low. Figure 4.1 shows the number of PNBS and ANBS for every station. For the big majority of stations, the number of ANBS reach at least half of PNBS.

One striking example is station 122, where just 3 stations out of possible 34 reach the criterion. That is due to the exposed location of the station at the Gleichenberger Kogel, at an altitude of around 520 m, which indicates that temperature development behaviour differs significantly from surrounding stations. For all the other stations, the accordance-criterion seems to bring an appropriate separation of PNBS and ANBS.

4.2.2. Relative Humidity

As the data quality of the available relative humidity daily data is worse than for temperature (see Table 4.2), it is not possible to apply the same approach of neighbouring selection as for temperature data. The reason for that bad data quality is that *"certain humidity sensors tended to underestimate relative humidity, especially for high values"*

[3] Candidate station means the station which is actually under investigation.

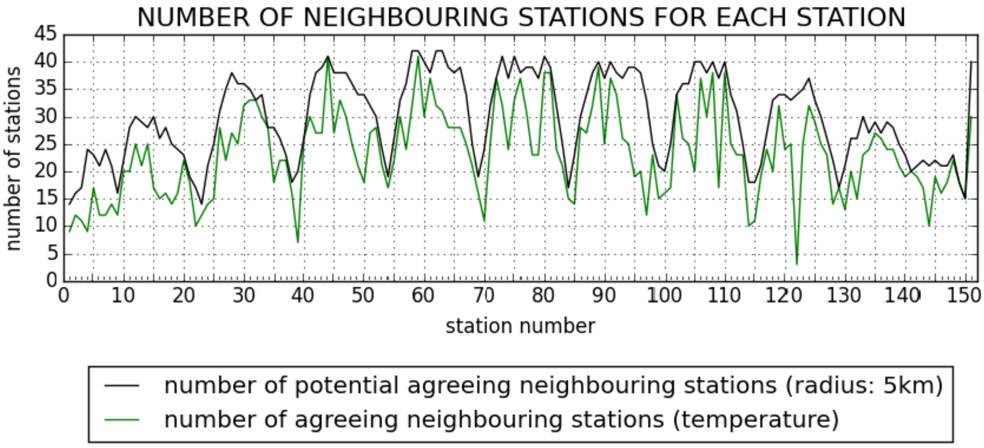


Figure 4.1.: Temperature analysis: Potential agreeing neighbouring stations (PNBS) (radius: 5 km) and agreeing neighbouring stations (ANBS) over all stations.

(Scheidl et al., 2017, p. 10). If this underestimation was strong enough, the QCS detected the corresponding values, which led to the overall bad humidity data quality (Scheidl et al., 2017).

Over the whole time range, only 56.24 % of all daily humidity data meet the Q-Flag-0 criterion, which is shown via the black curve in Figure 4.2. Furthermore, days of very few stations measuring correctly concentrate especially in autumns between 2009 and 2014. After TQ-sensor changes between 2013 and 2016 quality improved significantly. Caused by the bad quality during the mentioned earlier years and the to low robustness of taking interpolated neighbouring data (values with Q-Flag > 0) as reference[4], it is impossible to apply the 5 km-radius-criterion for the PNBS selection.

The red curve in Figure 4.2 gives an indication of how much PNBS would be available on average for each day over all stations. At many days in the mentioned problematic times, the number of PNBS would be at values well below ten, which would not provide robust enough reference values. Moreover, it would be impossible anyway due to not any available PNBS at some days for some stations.

In order to obtain enough PNBS to implement the analysis, it is therefore chosen to consider all available 150 WegenerNet stations as PNBS. The quality of the reference values in this case is still high enough, which is proved via Figure 4.3. Figure 4.3 shows that the standard deviation of the whole field daily data is just slightly above the average over all stations for the corresponding PNBS if the 5 km-radius-criterion would be chosen.

Similar to the temperature accordance-criterion selection of ANBS out of PNBS, ANBS are selected for the humidity analysis. In contrast to the temperature analysis, the PNBS pool is just filled with all stations as explained before. Furthermore, the accordance-criterion is set to 50 % in contrast to 10 % for the temperature analysis. That is on the one hand caused by the fact of more volatile humidity data, and on the other

[4]Why this is the case will be explained further on in Section 4.6.

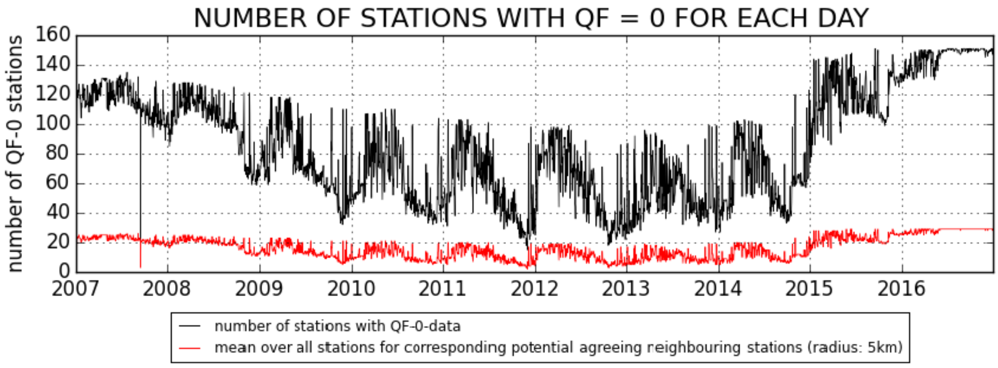


Figure 4.2.: Humidity analysis: The black curve depicts the number of stations which provide Q-Flag-0 values for each day. The red curve shows an average number of available PNBS over all station per day, by just using Q-Flag-0 reference values.

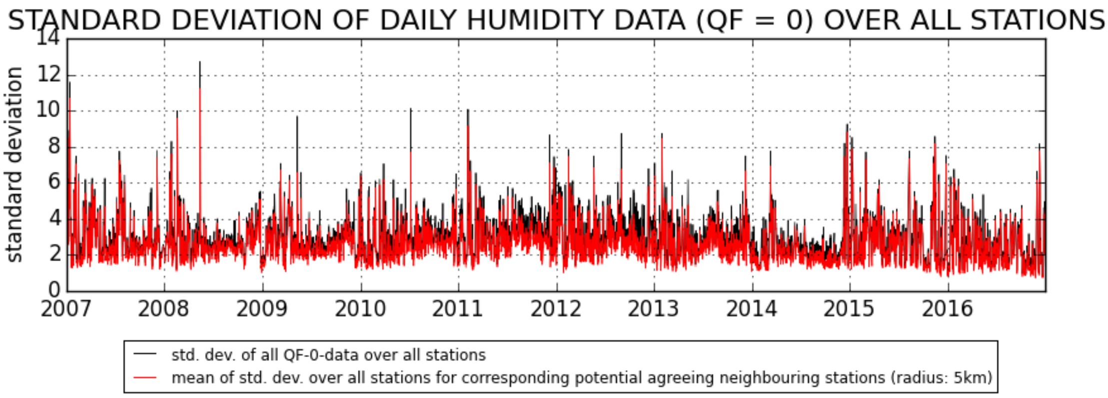


Figure 4.3.: Humidity analysis: The black curve depicts the standard deviation of the daily data over all stations. The red curve is an average over all standard deviations for all PNBS if the 5 km-radius-criterion would be applied.

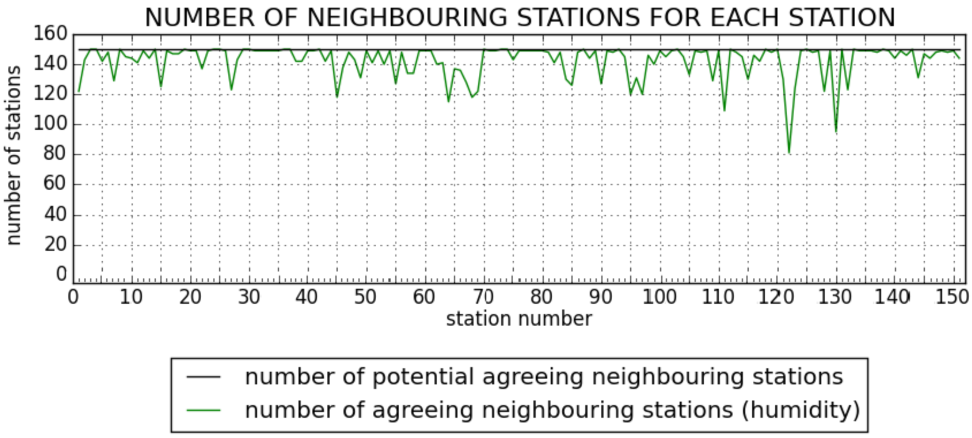


Figure 4.4.: Humidity analysis: Potential agreeing neighbouring stations (PNBS) (all stations) and agreeing neighbouring stations (ANBS) over all stations..

hand, it is inevitable due to the low availability of good quality daily data. For getting the status of an ANBS, for each station the following inequality has to hold:

$$\sqrt{\frac{1}{n}\cdot\sum_{i=1}^{n}[(p_i-c_i)-(\bar{p}-\bar{c})]^2} < 0.5\cdot\sqrt{\frac{1}{n}\cdot\sum_{i=1}^{n}(c_i-\bar{c})^2} \tag{4.2}$$

with:
p ... daily data of the PNBS
c ... daily data of the candidate station
i ... day
n ... number of days

Figure 4.4 shows the number of PNBS and the selected number of ANBS for the humidity analysis. The 50 %-accordance-criterion only eliminates on average a few PNBS with the exceptions of station 122 and 131, which eliminate about 70 respectively 50 stations. The reason for that is the special behaviour at their locations. Especially station 122 (Gleichenberger Kogel) is conspicuous again (see Subsection 4.2.1).

4.3. Formation of Increment

After defining ANBS, it is possible to calculate an increment over the whole time series. For this purpose daily median values of all ANBS for each day[5] are subtracted from daily temperature values of the candidate station. To improve the meaningfulness of the humidity increment, the increment is calculated by subtracting the daily median values

[5] The median is chosen due to its higher robustness compared to taking the mean.

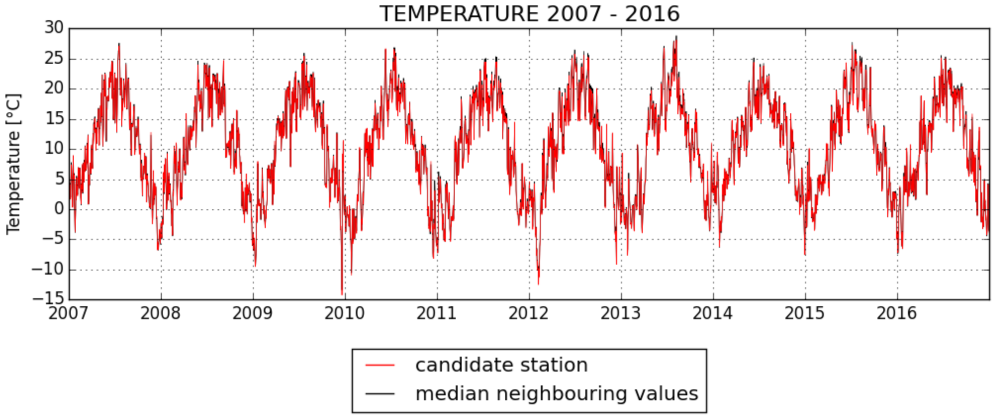


Figure 4.5.: Station 77: Temperature of candidate station and median of ANBS (the latter not well visible, since mostly shadowed by the candidate station observations.

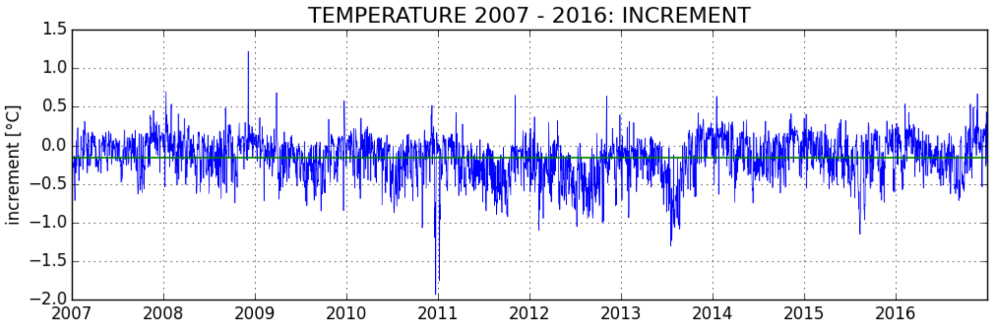


Figure 4.6.: Station 77: Temperature increment (blue curve) and corresponding mean (green line).

of all ANBS which provide Q-Flag-0 data for each day from the daily humidity values fo the candidate station. Section 4.4 describes which implications this special treatment of the humidity increment calculation brings for calculating correction values. Section 5.2 presents in more detail why this special treatment for the humidity data is necessary.

An exemplary visualization of that increment formation step is presented via Figures 4.5 and 4.6. It shows the temperature calculations of the reference station number 77. The blue curve in Figure 4.6 displays the calculated increment, which is in fact a subtraction of the black curve from the red curve depicted in Figure 4.5.

The green line in Figure 4.6 illustrates the increment mean over the whole time series. In this case the increment mean is slightly negative, which implies that station 77's location is on average slightly cooler compared to its near surroundings.

Another important variable is the standard deviation of the increment. Higher values imply a more individual development for a given station, which can be reasoned for

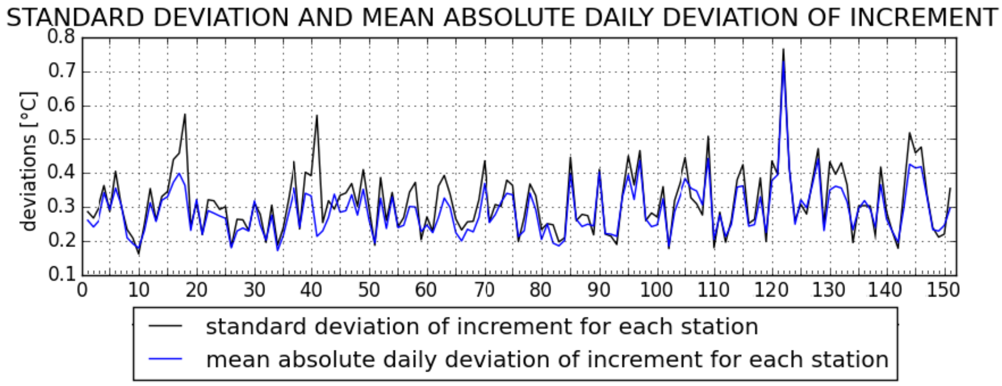


Figure 4.7.: Temperature: Standard deviation and mean absolute daily deviation of the increment for each station.

example by an relatively exposed location. The value for the standard deviation of station 77's increment is 0.27 °C, which is a typical value compared to all other stations.

Figure 4.7 shows the standard deviations of the temperature increment calculations for all the stations. It is shown that station 122 reaches the highest value (around 0.75 °C). This can be reasoned by its exposed location and the highest station altitude in the WegenerNet (520 m). Stations 18 and 41 follow with values around 0.55 °C. Reasons for that are location and sensor problems, which will be presented in more detail in the results part (Section 5.1). Figure 4.8 presents the standard deviation values for the relative humidity.

The blue curves in Figures 4.7 and 4.8 describe the mean absolute daily deviation of the increment. They help to make the interpretation of the standard deviation curves more meaningful. If the mean daily deviation is significantly lower compared to the standard deviation (most notably at station 18 and 41), the implication is that there exists at least one phase of a strongly positive or negative deviating increment in the time series with small daily internal fluctuations. Otherwise, if the mean daily deviation is similar to the standard deviation, it implies that there is no systematic deviating phase of the increment in the time series. Overall, this analysis provides on the one hand first hints for possible systematic change points and therefore for existing inhomogeneities. On the other hand, bigger differences between the two curves could also be an indication for local seasonal fluctuations at the corresponding candidate station.[6]

4.4. Cumulative Sums and Change Point Detection

By using the calculated increment, it is now possible to take the cumulative sum of the increment time series as Cowtan (2015) suggests. He uses the cumulative sum method from Taylor (2000). Applying the method on the calculated increment means first to subtract from every increment value the increment mean such that the sum over the

[6]A concrete explanation of this phenomenon will be given in Section 4.5.

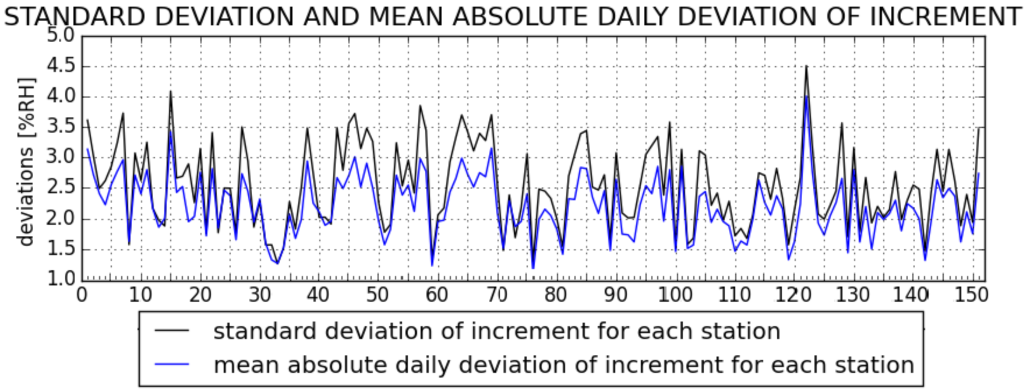


Figure 4.8.: Humidity: Standard deviation and mean absolute daily deviation of the increment for each station.

whole generated data time series is zero. Now, these values can be summed up over time. Taylor (2000) points out that what we get is not a cumulative sum of the original values, instead it is the cumulative sum of the differences between the values and the average. So, the cumulative sum plot starts with zero and has to end with a zero by definition.

Furthermore, Taylor (2000) notes that interpreting cumulative sum charts requires some practice. In general, it can be mentioned that a constantly upward tending trend in the cumulative sum plot implies that there is a period where the increment values lie constantly above the overall average and vice versa. Further, for example an increased upward trend implies upwards drifting increment values. In general, change points can be detected by reading out the maxima and minima of the cumulative sum curve, which can be interpreted as a change of the increment from above average to below average values and vice versa.

The black curve in the upper part of Figure 4.9 illustrates the cumulative sum for the calculated temperature increment of station 77 over the whole time series. As shown, there exits one maximum and one minimum turning point, respectively. The question now is how to be confident that these two points are real detected change points. To solve this, bootstrapping is done. For this purpose the cumulative sum values of the given increment time series are distributed into random increment time series. In our case this step is repeated 1000 times, which means that 1000 bootstrap paths are generated.[7] If a maximum/minimum turning point is found outside of all bootstrap paths, then there exists a confidence of around 99.9 % that a change took place. As the maximum and the minimum turning point in Figure 4.9 are both outside of the 1000 bootstrap paths, these two change points can be labeled as change points with a very high confidence. In general, the minimum confidence level for detected change points is fixed at 98 % to be sure of detecting change points with a high confidence.

[7] There was also done a test with 10000 bootstrap pathways. As the results did not change significantly, it was decided to generally apply 1000 bootstraps as the baseline.

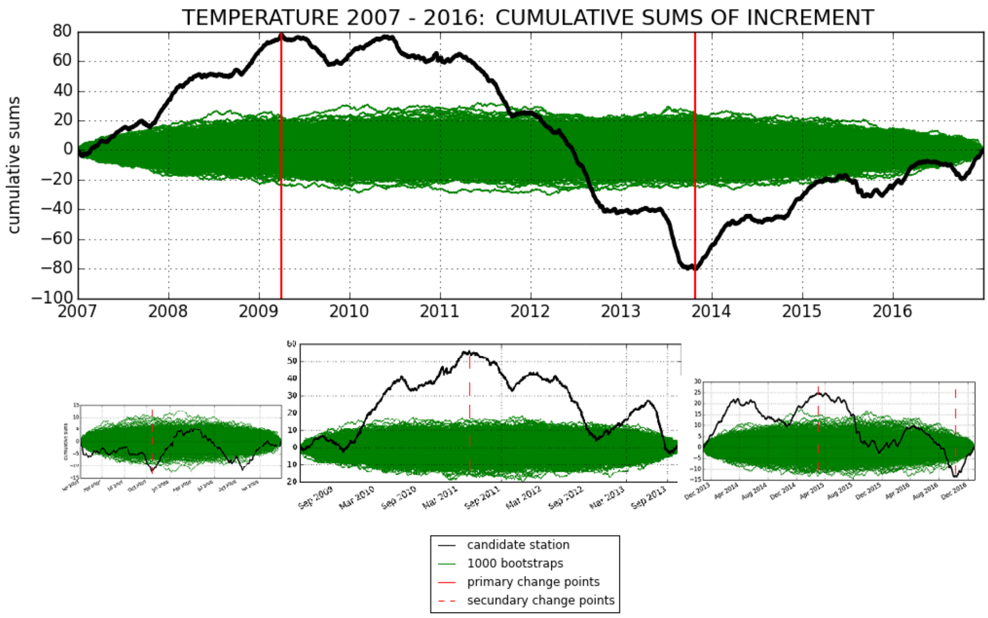


Figure 4.9.: Station 77: First order cumulative sum calculation of temperature increment with primary change points detected (top) and second order cumulative sum calculations with secondary change points (bottom).

For detecting further change points between the two primary change points, the time series is split up at the dates of the primary change points. Then the examination is repeated (again subtracting the mean of each sub-window before) as shown in the lower part of Figure 4.9. Further change points are marked now as secondary change points. To find more possible change points, this method is repeated five times (in our application), which implies continuously smaller time windows. At the end, many change points are detected, which is depicted in Figure 4.10. The higher the degree of the change point, the more likely the changes are reasoned by special weather conditions and therefore geophysical reasons.[8] Changes due to technical reasons – like sensor or location changes – are, due to their long-lasting deviations, mostly found by looking for primary or secondary change points (low-degree change points).

Cowtan (2015) states that this method of finding changes is a very simple one. The benefits lie in its simple implementation and reproduceability. Furthermore, the cumulative sums method is easy to visualize and therefore it is easy to understand.

After detecting all possible change points – due to different reasons – it is now possible to calculate offsets in the increment time series. Cowtan (2015) tested two different hypothesis of creating offsets. The first provides piecewise constant offsets between all detected change points by just compiling the mean of the increment time series between

[8]Stations partially work locally different, for example over the seasons, which causes higher degree changes during one year. Section 4.5 will treat those phenomena.

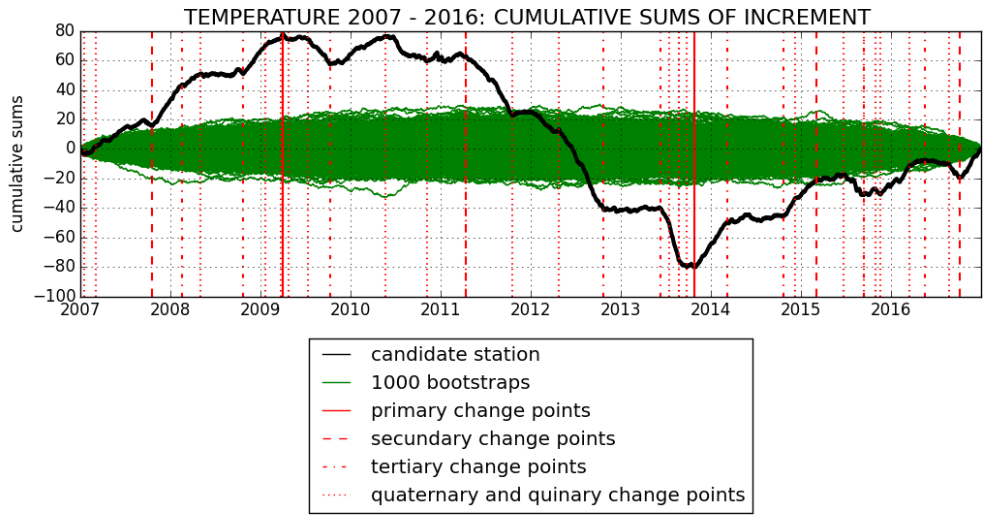


Figure 4.10.: Station 77: First order cumulative sum calculation of temperature increment and detected change points.

anay change points of interest. The second hypothesis is set up to create piecewise linearly approximated offsets, estimated by linear regression functions. Overall, the first hypothesis of using piecewise constant offsets fits better to the data in Cowtan (2015). Due to this observation and since we look for sensor-change effects and not gradual changes, this analysis uses the piecewise constant offset calculation, too.

Therefore, an increment mean is calculated between the different change points, which is shown for station 77 in Figure 4.11. The real dates of sensor or location changes of the station are introduced externally into this plot.[9] It is now possible to have a first rough overview of the different sensor behaviour. For our example station 77, the new sensor (since summer 2013) seems to work a bit warmer compared to its predecessor sensor. A calculation and a corresponding explanation of correction values is done in Section 4.6. However, before being able to compare old and new sensors, an observation of the stations location peculiarities, like local seasonal fluctuations, must be done, which is following next in Section 4.5.

4.5. Local Station Peculiarities and Seasonality

For the final calculation of correction values for eliminating inhomogenieties in the time series, it is important to get properly calculated means for the increment. As already explained in the previous Section 4.4, a lot of changes occur due to peculiarities and seasonality. In this section, an investigation of these time dependent fluctuations is done.

[9]During summer 2013 there was installed a substitute sensor at station 77 for around two months. Therefore in this case two dates of sensor change are drawn in Figure 4.11.

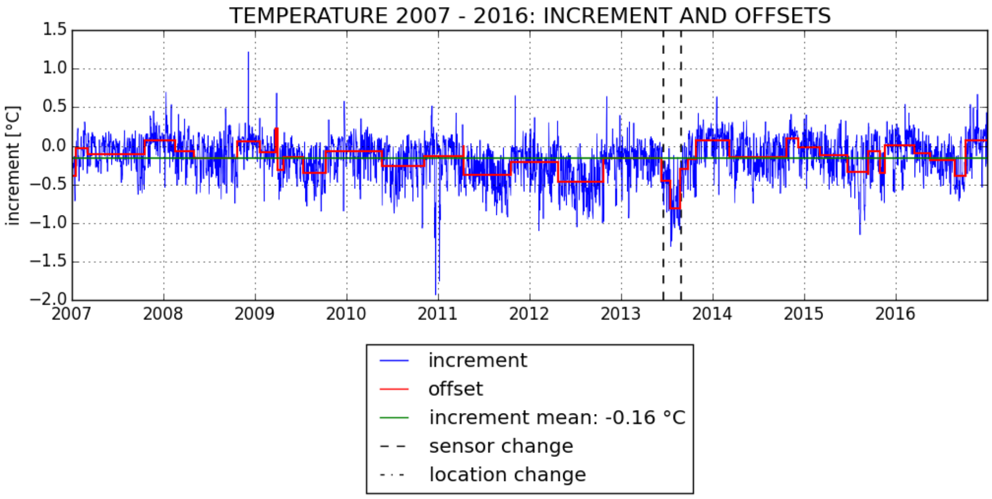


Figure 4.11.: Station 77: Temperature increment with corresponding mean and offsets. Real dates of sensor and location changes are drawn externally on the x-axis.

By analysing the curves of increment over the different stations, a clear seasonal dependence was detected. Overall, there exist notably oscillating increment time series with reaching relatively higher increment values during the summer half year or winter half year, depending on the peculiarities of the observed station. As already shown in Figure 4.11 for station 77, there exists a slight tendency of relatively higher temperatures during winters for this station[10]

A much clearer example of a local seasonal signal is provided by station 62 (see Figure 4.12). Obviously, at stations 62's location, summers are significantly warmer with respect to the winters, when comparing the station's temperature values with its ANBS. This effect implies very small scale (local) seasonality. Reasons for this could be for example flows of cold air in winters during inversion weather conditions or simply peculiarities of the exposure by sunshine at this station location. Furthermore, station 62 shows striking outliers during winters, with up to 3 °C lower temperatures compared to its ANBS, which is maybe due to cold air accumulation caused by the station's location on the valley floor at around 280 m.[11]

Another interesting effect can also be explained via stations 62's increment curve. During summer 2007 there exists a time range where no sensor was installed[12], which can be easily identified in Figure 4.12. Due to the relatively warmer summers at station 62, it was obviously not possible for the DPG to provide suitable temperature data for this station in summer 2007. However, a positive correction of the data in the mentioned time range in summer 2007 is desirable to reach better data quality. A calculation of the

[10]In Figure 4.11 two sensor changes are depicted in summer 2013. There was no location change.
[11]An examination of that winter temperature inversion effect is done in Subsection 5.1.4.
[12]The data in the mentioned time range is flagged by Q-Flag = 2.

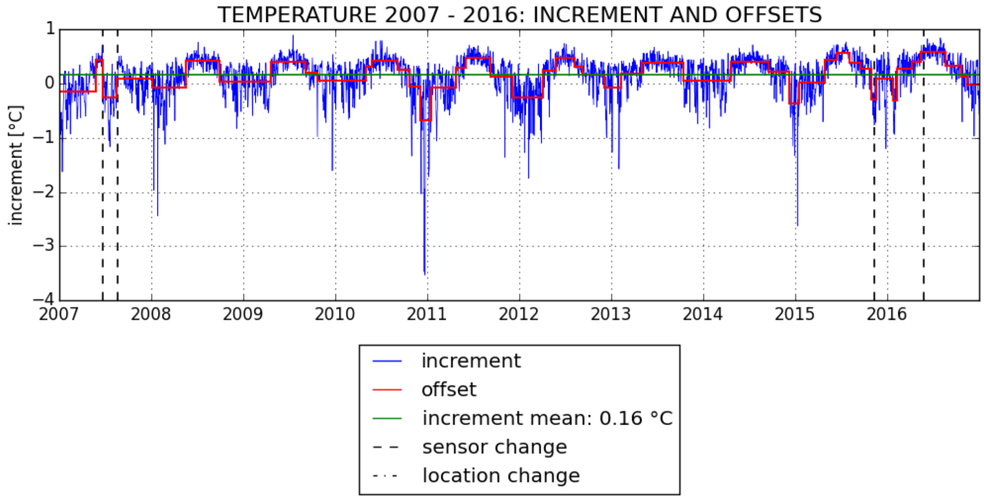


Figure 4.12.: Station 62: Temperature increment with corresponding mean and offsets.

specific correction value is presented further on in the results chapter in Section 5.1.3.

In general, to get comparable values for these explained seasonal fluctuations, a quantification is necessary. Therefore, a so-called seasonal coefficient is calculated by subtracting the mean of the daily increment values of the winter half year from the summer half year. The seasonal coefficient provides information of the warmth of the summer half year compared to the winter half year for each station relative to its ANBS. A zero would imply that there exists no local seasonal effect at the corresponding station. Station 62 for example provides the highest absolute value with +0.33 °C. Humidity data show local seasonal effects, too. For both (temperature and humidity) data sets see Tables A.5 and A.6 in Appendix A, which provide the seasonal coefficients for each station.

As a general consequence, calculating increment means over other than year-round periods can readily lead to distorted values. We therefore will define this as a criterion for an estimation of reliable correction values.

4.6. Correction Values and Homogenization

For correcting inhomogeneities in the time series due to sensor changes, a direct comparison between the before-sensor-change ("old") time series and the after-sensor-change ("new") time series is necessary. To get the systematic deviation of the new sensor compared to the old one, a "new" increment mean is calculated and subtracted from a calculated "old" increment mean. As, in general, the old sensor devices were calibrated, the old increment mean is taken as the reference value. So, possibly arising inhomogineities due to sensor changes are corrected via correction values for the new sensor.

For the temperature calculations it is possible to take the maximum number of available year-round sequences for calculating the old and new increment mean. This means that it is necessary to have at least one full year of increment development as well in the old time sequence as in the new one.

As the humidity data quality is much lower (see Table 4.2 in Section 4.1), it is not possible to do a simple year-round increment mean calculation. Overall, flagged daily humidity increment data values (Q-Flag = 1, 2 or 3) are on average lower compared to Q-Flag-0 data values (see Table 5.4 in Section 5.2). The most obvious reason for this effect seems to be that data is more vulnerable for getting flagged in times of very high relative humidity, which leads to dryer flagged data on average. Even though, this effect is low in its magnitude (see Table 5.4), including the data into the increment mean calculations for the sensor comparison would lead to significantly distorted results.

To solve this problem, a different framework is applied. At first, only Q-Flag-0 data go into the calculations for the sensor comparisons, which leads to the problem of getting randomly distributed data along and within years. Taking annual averages would of course violate the local seasonality phenomena (see Section 4.5). Due to this arising problem, a minimum number of days with Q-Flag-0 per month is introduced for the old/new increment mean calculation. This minimum is set to ten available days per month over the whole sensors time range. Then, the average increment value over all available Q-Flag-0 values for each month is calculated. The 10-days-minimum-limit therefore guarantees a representative value for each month. To end up with a final increment mean for the sensor, an average over all monthly averages is taken, by weighting the single values correctly regarding the number of days per month. Of course, these explained requirements have to hold for both, the old increment mean (old sensor) and the new one (new sensor).

At the end, one value for each station is provided, which is calculated by subtracting the new increment mean from the old one. The value can be interpreted as the theoretical correction value (or as the deviation of the new sensor compared to the old one by reversing the sign), which the new sensor would need to get added in order to run completely homogeneously on average compared to the old one. The sign of this theoretical correction value gives information of respectively the warmth/coldness and the moistness/dryness of the new sensor. A plus-sign indicates that the new sensor works colder/dryer compared to its predecessor and vice versa. The magnitude of the value gives information on the extent of the deviation.

To distinguish between real sensor inhomogeneities and coincidentally occurred smaller sensor deviations within the sensor's uncertainty (see Section 2.2), a threshold magnitude is defined and the calculated value is applied only if it exceeds this threshold. For the temperature threshold we chose 0.1 °C, for the relative humidity 1.8 %RH is defined. Both values represent the sensor's measurement uncertainty (tolerances according to technical specifications; see Section 2.2).

Next, the deviations are actually calculated. If the individual deviation (theoretical correction value) exceeds threshold of magnitude and the date of the actual sensor change matches with a detected low-degree (primary or secondary) change point, the calculated correction value gets the status of a necessary correction, which is recommended to be subsequently applied in order to homogenize the time series.

5. Homogenization Results and Evaluation

This chapter presents the results of the temperature and humidity data analyses. The central findings are represented by the recommended correction values to homogenize the newly implemented TQ-sensors with respect to their predecessors. Beyond that, a location homogenization was done for one station.

Furthermore, some special irregularities and particularities are found during the homogenization work, which are also shown in this chapter.

To verify the calculated corrections and suggestions of data homogenization and improvements, several linear trend studies are done in Section 5.3 over the ten years of existing WegenerNet data. The verification shows the differences between unhomogenized (original) data and homogenized data by applying the recommended correction values.

In the last Section 5.4, the explained change point detection method is applied on WegenerNet precipitation data to demonstrate the limits of the chosen method.

5.1. Temperature

This section incorporates results and possible corrections for temperature inhomogeneities due to sensor and location changes. Furthermore, it presents possible improvements for DPG-processed data with low-quality flags. Finally there is shown an interesting particularity in the WegenerNet, which is found in the course of the local temperature seasonality (see Section 4.5) at the different stations.

Figure 5.1 provides information about the temperature offsets for the most interesting stations, in terms of offset behaviour, which are also mainly treated in the following subsections.[1] The plotted offsets are calculated by subtracting the increment mean of the old (calibrated) sensor from the computed temperature offsets.

As an exception, station 41's temperature behaviour is not analysed in more detail. A sensor defect in 2011/2012 leads to the anomalous behaviour depicted in Figure 5.1. From analysing the latter, there already exist special correction values for station 41.

5.1.1. Inhomogeneities due to Sensor Changes

Table 5.1 shows all recommended temperature correction values for the stations which exceed the 0.1 °C threshold. If the value is positive, the new (uncalibrated) sensor measures too cold over a daily mean. Therefore a positive correction of the new sensor

[1]The full plots for all stations can be found in Appendix A (Figures A.1 and A.2).

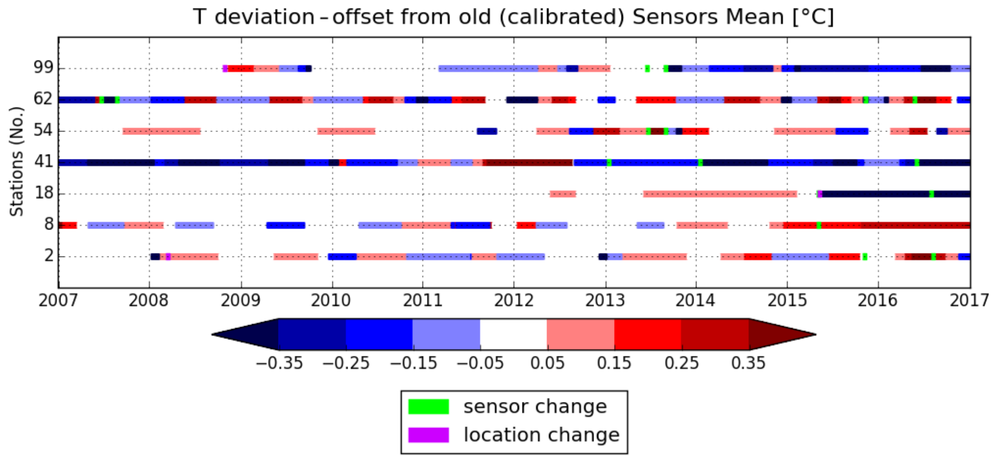


Figure 5.1.: Temperature offset development for selected stations.

is needed. If the value is negative, the new sensor measures too warm.[2]

Overall, 31 new sensors show significant (>|0.100| °C) deviations to their predecessors.[3] Out of these 31 sensors, 20 are confirmed by the change point analysis carried out. That means, that the date of the sensor implementation matches with a detected primary or at least secondary change point. For another total of 31 stations, it was not possible yet to calculate any sensor deviation due to the too short running time of the newly installed sensors.[4]

As an example for a necessary sensor correction, see Figure 5.2 of station 99's analysis. As shown in Table 5.1 a relatively high correction of +0.24 °C of the new sensor (since 2013-08-29) is necessary.

By calculating the mean deviation of the new sensors over all observable stations[5], no systematic deviation of the new sensors compared to their predecessors is visible. The collective mean deviation of the new sensors amounts to –0.02 °C, which means that the new sensors measure a bit too cold on average. The corresponding standard deviation over all deviations is 0.09 °C, which shows that the mean deviation constitutes no significant deviation.

Due to seasonal fluctuations (see Section 4.5), for some stations the detected primary or secondary change point deviates some weeks or at most a few months from the date of the sensor implementation. This is the case if a natural seasonal change in one direction (warmer or colder) is compensated by a technical sensor deviation in the opposite direction. Then, the corresponding change point will be detected either at the beginning

[2]The theoretical temperature correction values for all stations are shown in Tables A.1 and A.2 in Appendix A.

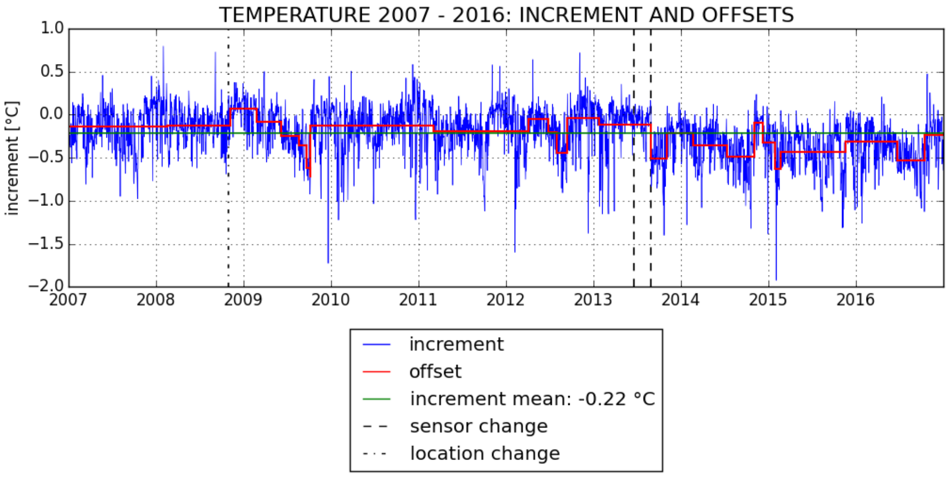
[3]For the correction values of stations 133 and 135, the processing problems (see Subsection 5.1.3) are already included in the calculation.

[4]Sensors, which were changed during 2016.

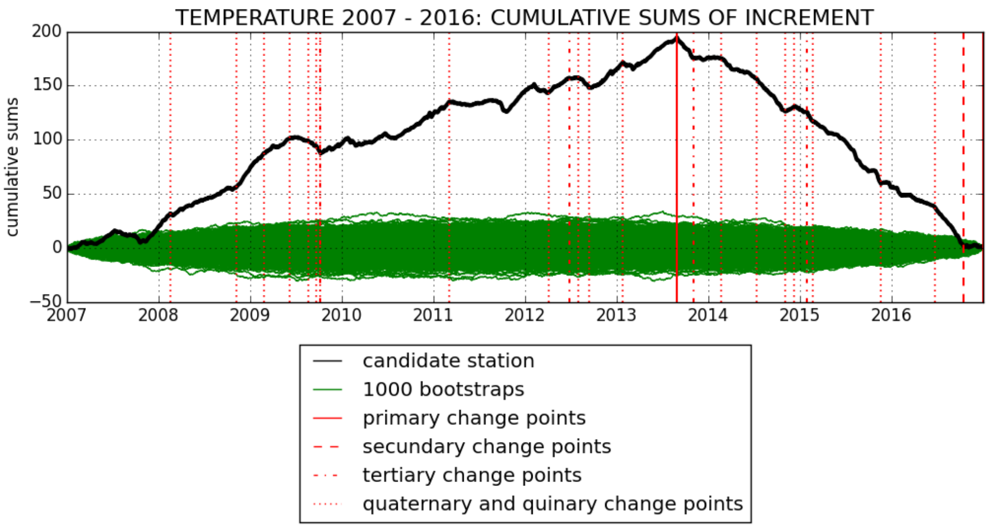
[5]Overall 119 stations are incorporated. In addition to the 31 not yet observable stations, station 18 is excluded in this calculation due to its special location change problems (see Subsection 5.1.2).

Table 5.1.: Temperature: Recommended Correction Values of new TQ-sensors

Station ID	**Sensor Implementation**	**Correction Value (°C)**	**Confirmed by Change Point Detection**
6	2013-08-29	0.23	yes
8	2015-05-06	-0.28	yes
14	2014-10-20	0.15	yes
16	2015-01-14	-0.19	yes
17	2015-11-10	0.10	no
26	2015-01-15	-0.13	yes
35	2015-11-13	-0.14	no
48	2015-01-13	-0.11	no
63	2015-04-27	0.17	yes
70	2014-10-27	0.17	yes
71	2015-04-30	0.11	yes
72	2013-08-30	0.19	yes
75	2014-10-28	0.13	yes
76	2015-05-04	0.15	yes
79	2015-05-13	0.14	yes
82	2013-08-29	0.18	yes
86	2015-05-06	0.10	no
99	2013-08-29	0.24	yes
100	2015-01-12	0.10	yes
101	2013-08-30	0.13	yes
109	2014-10-22	0.10	no
120	2015-01-16	-0.11	no
122	2014-10-19	0.12	no
126	2015-11-11	0.13	yes
131	2015-01-13	-0.24	yes
133	2015-01-14	0.10	no
135	2013-08-29	0.25	yes
139	2014-10-18	-0.10	no
144	2015-11-04	0.15	no
146	2015-01-13	-0.16	no
148	2015-11-10	0.11	yes



(a) Station 99: Temperature increment, increment mean and corresponding offsets.



(b) Station 99: First order cumulative sum calculation of temperature increment and detected change points.

Figure 5.2.: Station 99: Temperature increment and cumulative sum analysis.

Table 5.2.: Likely necessary future corrections of new temperature sensors.

Station ID	Date of Sensor Implementation	Direction of likely Correction
41	2016-06-01	positive
113	2016-06-02	positive
117	2016-06-06	positive
130	2016-05-30	negative
138	2016-06-03	positive

of a new season before the sensor change or at the end of the season following the date of the sensor change.

Figure 5.3 of station 8's analysis shows such an example. As there exists a seasonal fluctuation (relatively warmer winters compared to summers – see Table A.5) and the new warmer sensor was implemented at the beginning of June 2015, the effect of the locally relatively cooler summer was compensated by a warmer measuring of the new sensor. As illustrated in Figure 5.3, the primary change point was therefore found already at the beginning of the colder season in late autumn 2014. In addition, the strong upward trend of the cumulative sum curve since the sensor change in June 2015 indicates a clear inhomogeneous behaviour.

For all the 20 method-confirmed sensor deviations, an overall correction (beginning with the date of the new TQ-sensor installation) by the correction values depicted in Table 5.1 is recommended.

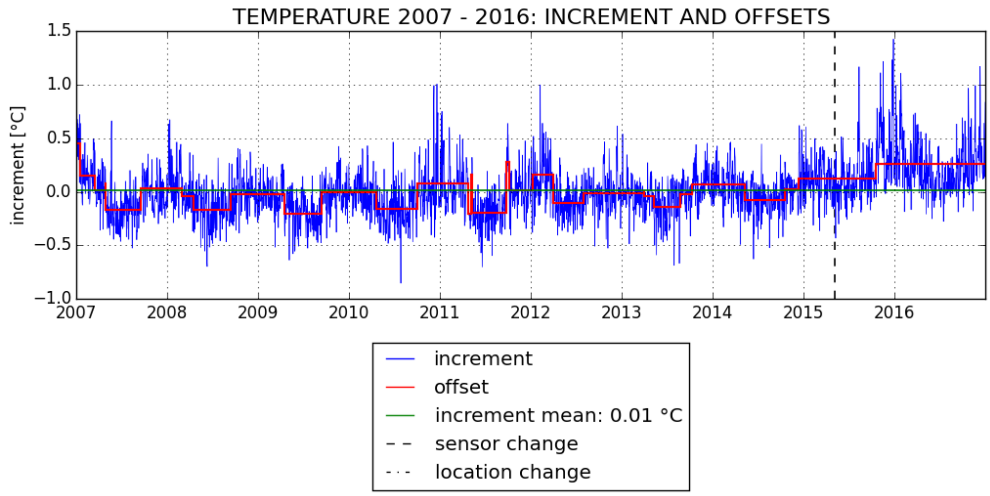
For the eleven not confirmed deviations (from Table 5.1), it is recommended to study their further development in the near future. An immediate correction of these sensors would possibly generate new inhomogenieties in the time series.

Table 5.2 presents all stations where a correction in the future looks likely. These five listed stations are out of the pool of those 31 stations, at which the TQ-sensor change took place during 2016 and therefore the new sensors running time is too short for a meaningful comparison, which needs at least a full year of new data. A further observation of these sensors is recommended, to correct them as soon as possible (at earliest in June 2017) if necessary.

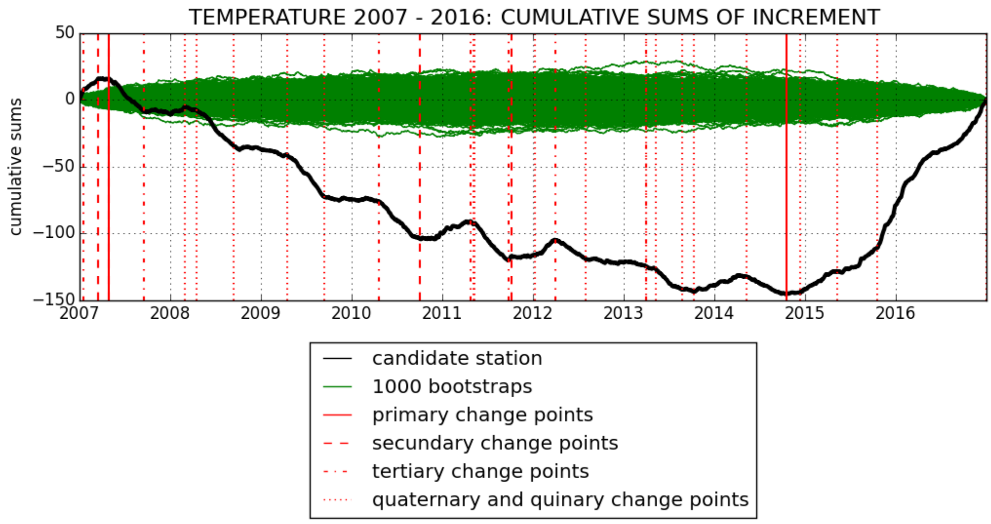
5.1.2. Inhomogeneities due to Location Changes

Beyond arising inhomogeneities due to newly implemented sensors, location changes of stations can also cause inhomogeneities in the time series due to different geophysical conditions at the new station's location. As a solvent example, after a sensor and location change (at the same time) in August 2013, station 18 shows a very different behaviour of the temperature increment (see Figure 5.4). On the one hand, the mean deviation of the new increment amounts to –1.09 °C, which indicates that the new location of station 18 is much colder. On the other hand, the new increment development is much more volatile, i.e., the time series is much more variable at the new location.

First, it was not clear if the changes in the behaviour are due to the new sensor or

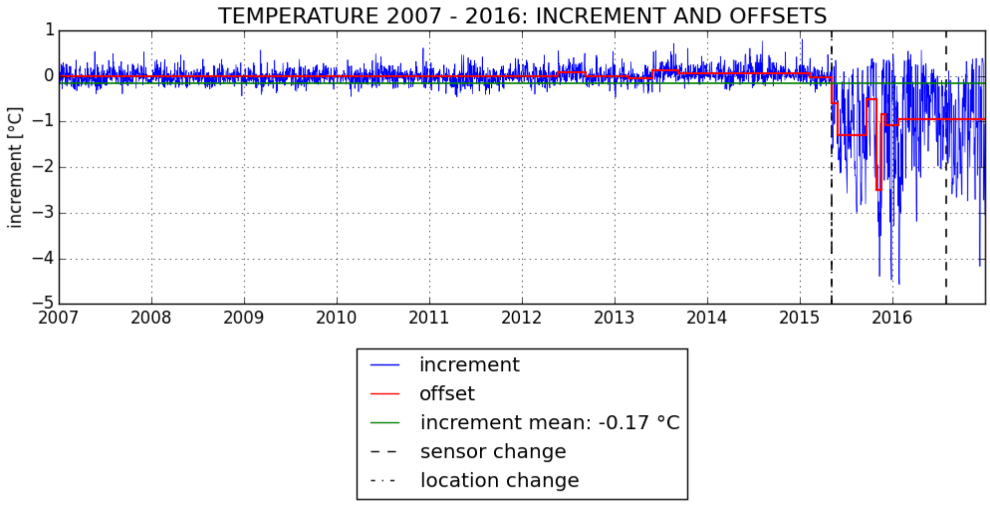


(a) Station 8: Temperature increment, increment mean and corresponding offsets.

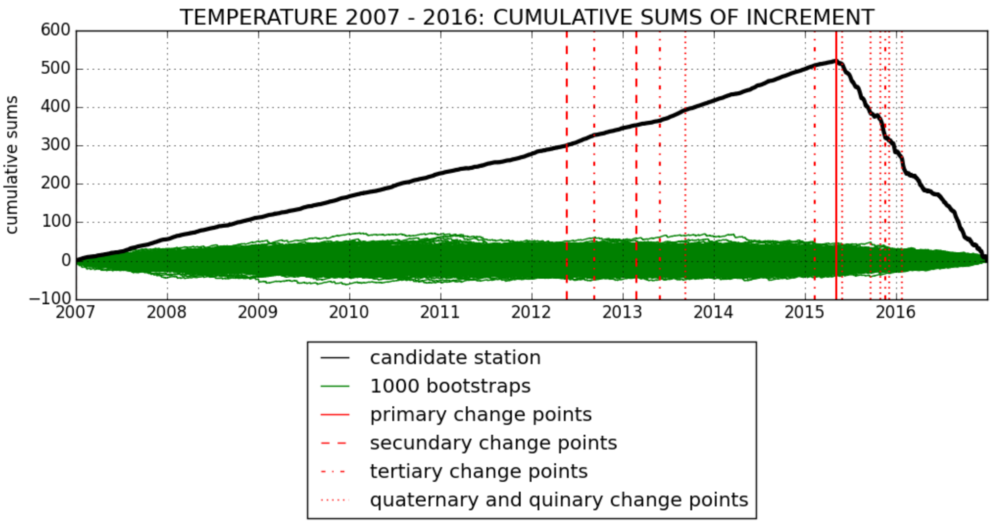


(b) Station 8: First order cumulative sum calculation of temperature increment and detected change points.

Figure 5.3.: Station 8: Temperature increment and cumulative sum analysis.



(a) Station 18: Temperature increment, increment mean and corresponding offsets.



(b) Station 18: First order cumulative sum calculation of temperature increment and detected change points.

Figure 5.4.: Station 18: Temperature increment and cumulative sum analysis.

due to the new location. After changing the sensor again in July 2016, it was clear that the new location led to this completely different temperature behaviour, as the recent sensor change causes no effect in increment development (see Figure 5.4).

For a correct homogenization, it is recommended as one option in this exceptional case to homogenize the old data time series until 2015-05-06 by a correction of –1.09 °C. This correction ensures to provide correct homogeneous mean temperature data, which is necessary for setting up climatological linear trend studies. Of course, this homogenization intervention just corrects mean temperature values and does not produce daily fluctuations, like the new location conditions generate. An alternative option is therefore to declare the old station closed and to separately declare the new station as a freshly started different station.

5.1.3. Processing Problems and Defective Sensors

As already mentioned in Section 4.5, data processing via interpolation from gridded data during times of no installed sensors can fail due to local station peculiarities and seasonality. Table 5.3 provides correction values for those critical processing time ranges. These values are calculated by comparing the increment mean of the corresponding time range with the increment mean of the same time ranges over all other available years. This intrastational method guarantees a best possible reflection of the stations peculiarities and also of the stations seasonal behaviour.

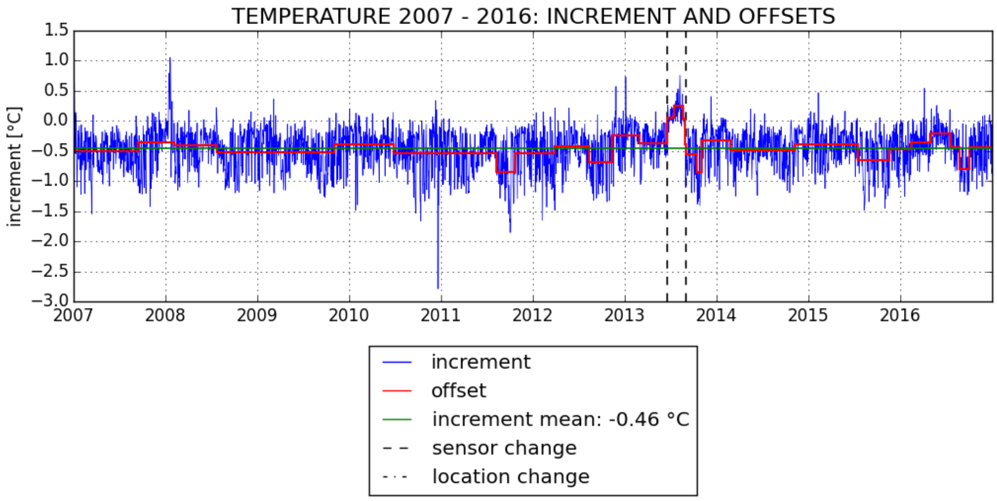
As an example, in Section 4.5 a necessary correction of the time range for station 62 in summer 2007 was already mentioned (see Figure 4.12). The concrete recommended correction amounts to +0.69 °C (see Table 5.3). The relatively high correction needed can be reasoned by the normally warm summers at station 62, which is impossible to obtain by interpolation out of data from surrounding stations and gridded data.

Another example is depicted in Figure 5.5: In summer 2013, there was no sensor installed at station 54 for about two months, which causes processed data with Q-Flag = 2. Due to the fact that station 54 is relatively cold compared to its neighbouring stations (increment mean = –0.46 °C), a correct spatial interpolation processing of temperature data fails. A correction of –0.64 °C for the corresponding time range is recommended (see Table 5.3).

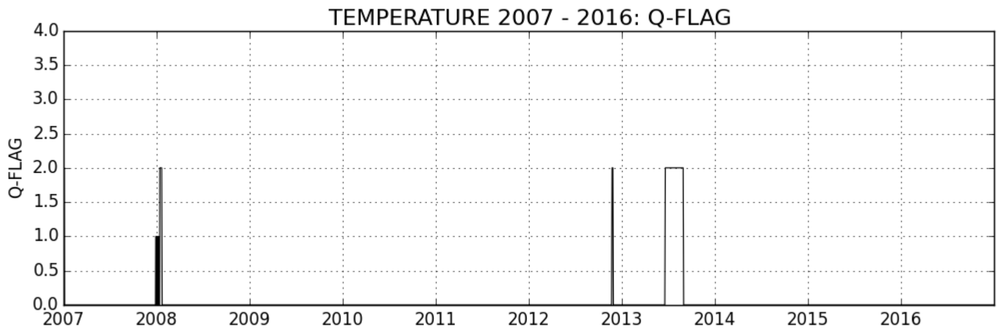
During the work, station 2's new temperature sensor (not part of Table 5.3) showed a problematic upward drift during 2016. It was decided to change the sensor again in August 2016. As shown in Figure 5.6, the increment behaviour has been normal again since this second sensor change, which implies that the installed sensor (2015-11-05–2016-08-05) was defect. It is recommended to re-process this whole time range at station 2 due to the unclear beginning date of the sensor defect.

5.1.4. Particularities in the WegenerNet FBR

In the course of the seasonality analysis (see Section 4.5), it was striking that stations located at higher altitudes showed warmer behaviour in many cases, especially in winters. To verify this, a simple altitude-temperature correlation was done.



(a) Station 54: Temperature increment, increment mean and corresponding offsets.



(b) Station 54: Q-Flags of daily temperature data.

Figure 5.5.: Station 54: Temperature increment and corresponding Q-Flags.

Table 5.3.: Temperature: Recommended Correction Values for deviating Processing Times

Station ID	Processing Begin	Processing End	Correction Value (°C)
6	2013-06-18	2013-08-29	–0.21
13	2010-01-04	2010-04-14	–0.46
15	2013-06-19	2013-10-29	–0.32
54	2013-06-19	2013-08-30	–0.64
62	2007-06-23	2007-08-21	0.69
65	2015-11-25	2016-05-26	0.16
66	2015-11-05	2015-11-30	0.51
82	2013-06-20	2013-08-28	0.31
132	2013-06-19	2013-08-28	0.20
133	2015-08-23	2015-12-07	0.55
135	2007-08-29	2007-11-07	0.65

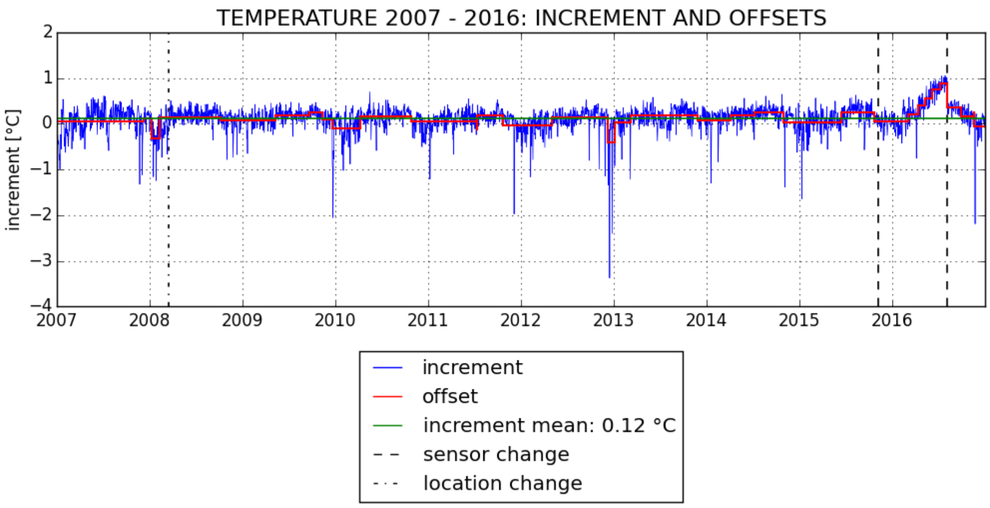


Figure 5.6.: Station 2: Temperature increment with corresponding mean and offsets.

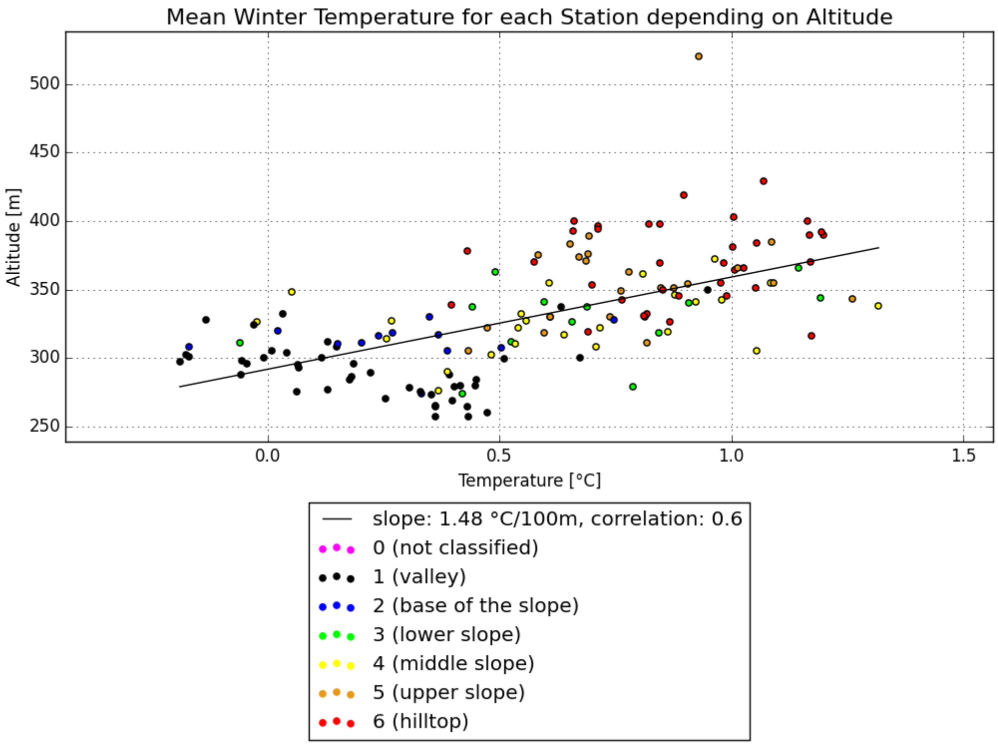


Figure 5.7.: Correlation of station mean winter temperatures and station altitude.

In Figure 5.7 every station's mean winter temperature (over all nine available winters) is plotted against its altitude above sea-level. As already described in Section 2.1, the 151 stations are located at altitudes between 260 m and 520 m. The stations are marked in different colours indicating their location classes (see Table 2.2). The plotted linear correlation line depicts an interesting positive vertical gradient (temperature rises with sea-level), which implies that the temperature gradient represents inversion behaviour. The concrete slope for the mean winter temperature data is 1.48 °C per 100 m. The correlation coefficient of the 151 plotted stations is 0.60 and therefore significant. By analysing the other seasons, there also exist positive vertical gradients, but without significant correlations >0.50 (spring: 0.38, summer: 0.28, autumn: 0.46).

By having a closer look at Figure 5.7, it can be seen that the valley stations tend to show a negative (normal) correlation. Furthermore, the outlier in this plot (520 m, around 0.9 °C) represents station 122 (Gleichenberger Kogel). By combining these facts, it seems plausible that there exists in average an inversion layer in the WegenerNet in about 300–400 m. Below and above this thin layer, imprinted by the hilly topography, a negative (normal) temperature gradient might be the case.

Overall, it seems that frequent temperature inversions are the dominant phenomena for forming the mean temperature gradient, especially in winters. That is, it appears plausible that winter days with inverted temperature conditions are inverted strong

Table 5.4.: Relative humidity: Mean deviations of increment values for different Q-Flags.

Q-Flag	Deviation [%RH]	Standard deviation [%RH]
0	+0.27	2.7
1	–0.25	2.9
2	–0.40	2.1
3	–2.99	1.7

enough to influence the mean winter temperature to a considerable degree. To get a better understanding of all the possible different reasons for this particularity, further research in this field is needed.

5.2. Relative Humidity

This section incorporates results and possible corrections for relative humidity inhomogeneities due to sensor and location changes. As already mentioned in Sections 3.1 and 4.6, there exists a tendency of a positive correlation between the data quality and the magnitude of the relative humidity values (especially in autumns and winters). To verify this phenomenon, Table 5.4 shows the mean deviations (over all stations) from the individuals station mean increment of each Q-Flag-value's mean increment. As shown, flagged values (Q-Flag = 1, 2 or 3) deviate significantly from Q-Flag-0 values. Most important are Q-Flag-1 and Q-Flag-2 values, because of their relatively high proportion of the whole daily data set (43.78 %, see Table 4.2). Table 5.4 also shows the corresponding standard deviations of the increment values, which inform about the degree of volatility, which is not so different between Q-Flag classes.

This systematic negative deviation of higher leveled Q-Flag-data is likely caused by the fact, that relative humidity values getting flagged with higher probability, if the relative humidity is often very high (above 90 %RH), which is the case most frequently in autumns and winters (see Figure 3.2).

This phenomenon causes problems for detecting change points with the help of the explained method. It leads in particular to the problem of detecting low-degree change points in times of data quality changes, which can hide the more interesting changes in the behaviour due to newly installed sensors. Therefore detected change points have to be interpreted more carefully.

Figure 5.8 provides information about the humidity offsets for the most interesting stations, which are also mainly treated in the following subsections.[6] The plotted offsets are calculated similar to the temperature offsets in Figures A.1 and A.2. Overall, the time range of the lowest data quality (2010–2014) show the lowest relative humidity offset values (marked in red, see also Figures A.3 and A.4 in Appendix A).

In contrast to the temperature sensors, the old humidity sensors were not calibrated. Furthermore, the old increment mean (reference value) is calculated by taking the mean

[6] The full plots for all stations can be found in Appendix A (see Figures A.3 and A.4).

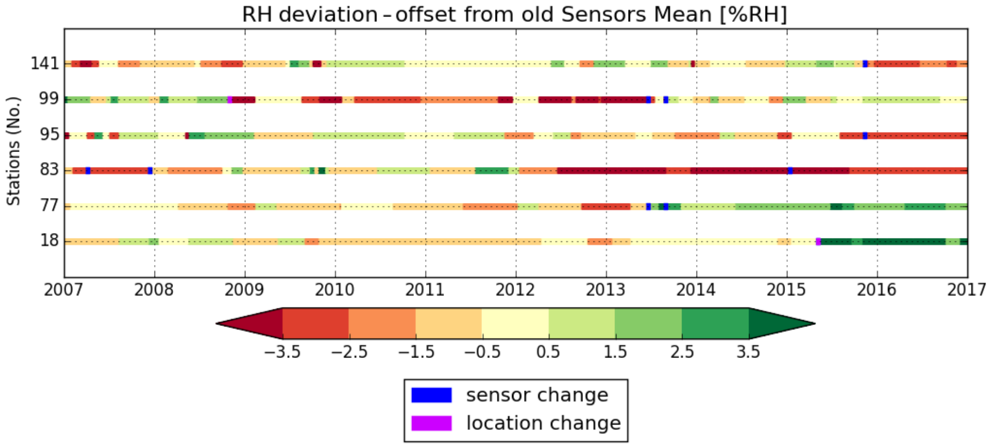


Figure 5.8.: Humidity offset development for selected stations.

only out of Q-Flag-0 values (see Section 4.6). Therefore, offsets plotted in Figures 5.8, A.3 and A.4 do not sum up to zero for the old sensors time range, in contrast to the temperature plots (see Figures A.1 and A.2 in Appendix A).

For 19 stations it is not possible overall to calculate any sensor deviation due to failing to achieve the 10-days-minimum-limit per month of the old sensor. Therefore, there are no offsets plotted in Figures A.3 and A.4 for these 19 stations.

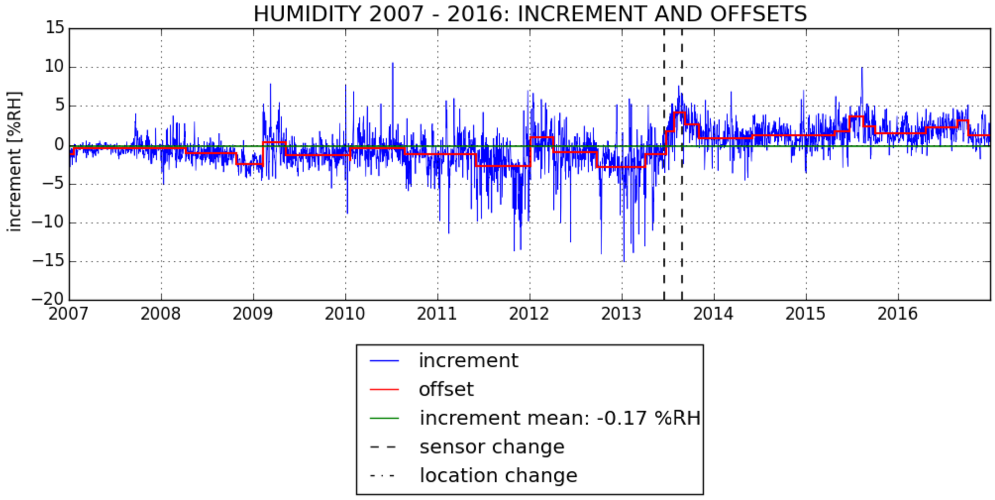
5.2.1. Inhomogeneities due to Sensor Changes

Table 5.5 shows all recommended humidity correction values. If the value is positive, the new sensor measures too dry over a daily mean. Therefore a positive correction of the new sensor is needed. If the value is negative, the new sensor measures too moist of course.[7]

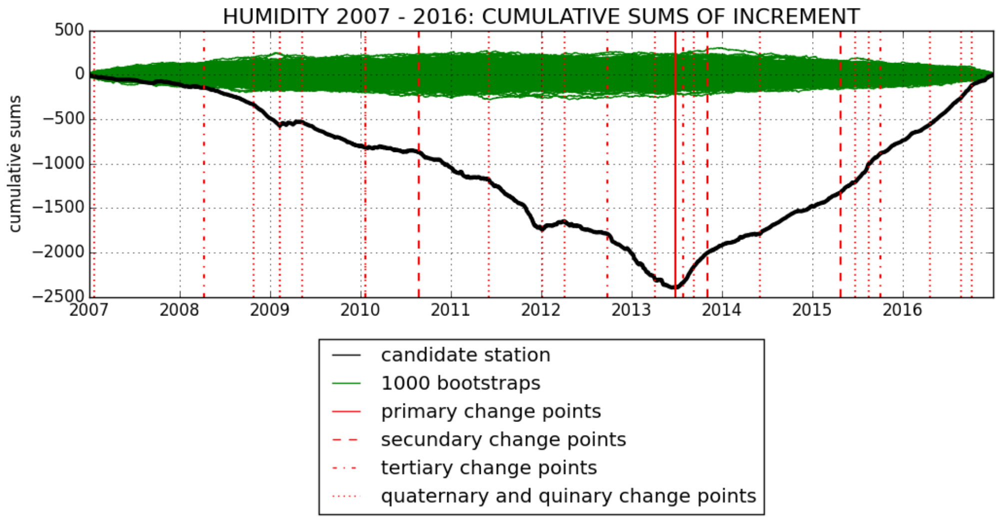
Overall, eleven new sensors show significant (>|1.80| %RH) deviations with respect to their predecessors. Even though the interpretation of the cumulative sums of the increment is much more difficult due to the systematically negative deviations of flagged daily data values, all sensor deviations which exceed the 1.8 %RH-threshold are confirmed by the applied method. Therefore, it is recommended to incorporate the suggested correction values (Table 5.5) in a next re-processing.

As an example, see Figure 5.9 of station 77's (reference station) analysis. As shown in Table 5.5, a negative correction (–2.0 %RH) of the new sensor (since 2013-08-29) is needed. The plotted daily Q-Flag values illustrate the bad humidity data quality until the sensor change. Nevertheless, it was possible to extract enough Q-Flag-0 values for each month to calculate a representative increment mean (reference value) for the old sensor.

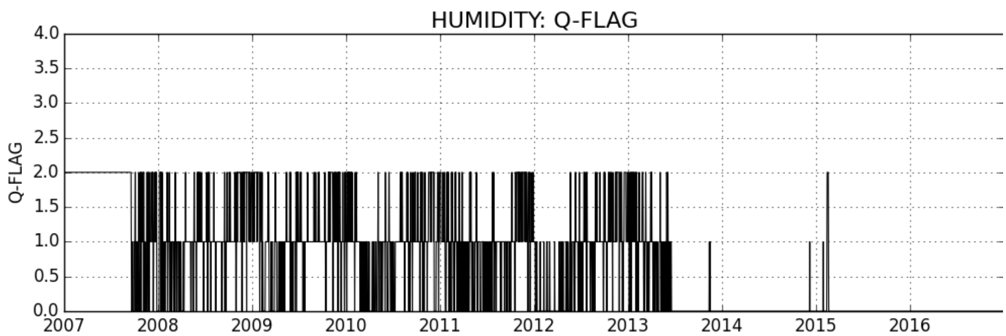
[7]The theoretical humidity correction values for all stations are shown in Tables A.3 and A.4 in Appendix A.



(a) Station 77: Humidity increment, increment mean and corresponding offsets.



(b) Station 77: Cumulative sum calculations of humidity increment, and detected change points.



(c) Station 77: Q-Flags of daily humidity data.

Figure 5.9.: Station 77: Humidity increment and cumulative sum analysis with corresponding Q-Flags.

Table 5.5.: Humidity: Recommended Correction Values of new TQ-sensors

Station ID	**Date of Sensor Implementation**	**Correction Value (%RH)**	**Confirmed by Change Point Detection**
35	2015-11-13	2.0	yes
77	2013-08-29	–2.0	yes
83	2015-01-15	3.4	yes
86	2015-05-06	2.0	yes
95	2015-11-11	2.6	yes
97	2015-05-05	2.3	yes
106	2015-11-12	2.5	yes
129	2015-01-14	1.9	yes
141	2015-11-11	2.6	yes
146	2015-01-13	2.3	yes
150	2014-10-20	1.8	yes

Beyond the fact of the lower Q-Flag-0 values of the old sensor compared to the new ones, it should be mentioned that flagged values (Q-Flag = 1 or 2) of the old sensor, which are on average lower compared to Q-Flag-0 values (see Table 5.4), strengthen the illustrative impression of the relatively drier old sensor, which has no effect on the calculated correction value.

Especially for the cumulative sum plot, this extra effect forces the method to find the shown primary change point on 2013-06-18. Therefore, it is overall necessary to interpret this plot carefully. Of course, these two effects ((1) drier old sensor and (2) lower flagged values within the old sensors time range) coincidentally act in the same direction in this case.

In the time range between 2013-06-18 and 2013-08-29 a replacement sensor was installed at station 77. As this sensor seems to show a similar behaviour compared to the new sensor, it is also possible to correct this shorter time range by the same correction value.

Except of station 77's humidity sensor, Table 5.5 shows only positive needed corrections. Nevertheless, the mean deviation over all calculable stations shows no systematic deviation (but even a trend) of the observable new sensors with respect to their predecessors. The overall deviation of the new sensors amounts to –0.52 %RH[8], which means that the new sensors tend to measure dryer with respect to their predecessors. The corresponding standard deviation over all deviations is 1.01 %RH, which is, however, high enough to ignore the new sensors mean deviation as being not sufficiently significant. Furthermore, the median deviation amounts to –0.40 %RH, which indicates that nega-

[8]Station 18 is excluded from this calculation due to its location change problems (see Subsection 5.1.2).

Table 5.6.: Likely necessary future corrections of new humidity sensors.

Station ID	Date of Sensor Implementation	Direction of likely Correction
87	2016-06-07	positive
105	2016-06-01	positive
111	2016-05-31	positive
123	2016-06-07	positive
140	2016-06-06	positive

tive deviations of the new sensors are less but higher in their magnitude, which leads to mainly positive correction values (see Table 5.5).

Table 5.6 shows stations where a necessary future correction seems likely. Similar to the temperature analysis, the mentioned five sensors are derived out of the pool of those 31 stations, at which the TQ-sensor change took place only during 2016. Therefore, a correction is possible at earliest in June 2017.

For three out of those 31 stations, it is neither possible to calculate an old increment mean due to the bad data quality[9] nor to calculate an increment mean of the new sensor due to the recent sensor change.

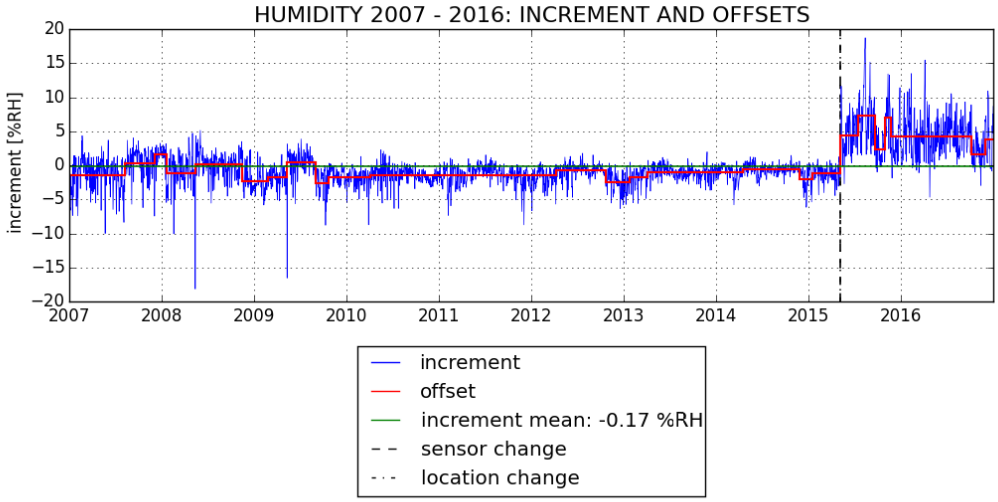
5.2.2. Inhomogeneities due to Location Changes

Subsection 5.1.2 already presented the necessary temperature correction of station 18's old location. Also for the relative humidity of the new location of this station, the behaviour deviates significantly from the old one (see Figure 5.10). The needed correction of the old location amounts to +5.2 %RH until the sensor change on 2013-06-05. Between the time range of 2009-09-02 (secondary change point) and the sensor change (2013-06-05, primary change point) almost all daily data values are flagged, which can be seen easily in both panels of Figure 5.10 by the "flat behaviour" during this time.

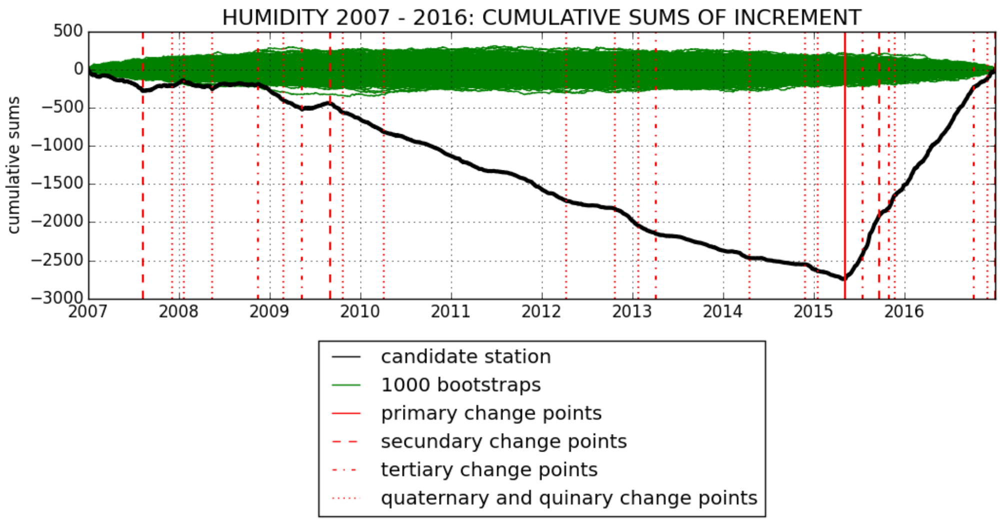
5.2.3. Problems with Corrections of Relative Humidity Data

By applying the recommended positive correction values in Table 5.5 and the location homogenization at station 18, problems will arise at a few days with very high daily relative humidity values. In concrete, high positive correction values (especially for station 18) will cause theoretic daily relative humidity values larger than 100 %RH, which is of course unrealistic and moreover essentially impossible. To solve this problem, it is recommended either to correct those daily values up to a maximum of 100 %RH, which is the simplest solution, or to apply non-linear correction values, which for example are negatively correlated with the magnitude of the individual daily relative humidity data values. To find the most appropriate application, a more detailed research based on the data is required.

[9] Overall, that is the case for 19 stations, as already mentioned.



(a) Station 18: Humidity increment, increment mean and corresponding offsets.



(b) Station 18: First order cumulative sum calculation of humidity increment and detected change points.

Figure 5.10.: Station 18: Humidity increment and cumulative sum analysis.

5.3. Verification of Correction Values by Linear Trend Studies

To demonstrate the necessity and at the same time the utility of the recommended corrections for improving the accuracy, this subsection presents two representative examples of linear trend studies over the ten years of WegenerNet data, in which the suggested correction values are incorporated.[10]

The first example shows the application of the temperature correction at station 99, which is already treated in subsection 5.1.1. For the second example, the application is done for the humidity correction at station 77, at which the found inhomogeneity is also already explained in detail in Subsection 5.2.1. For both examples, the recommended correction values are incorporated into annual and seasonal data.

Figure 5.11 illustrates a linear trend analysis for the anomalies of unhomogenized (original) and homogenized mean annual temperature.[11] Furthermore, the temperature anomalies for the WegenerNet regional annual mean is plotted. It shows that the homogenized curve (green) fits much better to the WegenerNet regional mean curve in contrast to the unhomogenized red curve. Moreover, the applied homogenization brings the linear trend almost to the same level as the WegenerNet regional mean trend. Of course, it is not the target to homogenize trends over the different stations, because of the possible different behaviour of the different stations. However, as an example, Figure 5.11 provides an easy and descriptive way to verify the homogenization of the new sensor at station 99, and anyway averaged station temperature data are clearly quite representative for the regional mean data.

Furthermore, Figure A.5 (in Appendix A) shows the same approach for all different seasons (application of the suggested correction value on seasonal data) of station 99. As shown there, the accuracy from the applied homogenization is as well very good for the for all different seasons.

In general, the found linear trends are not significant with respect to actual climate trends, of course, due to the short time range.

Figure 5.12 illustrates the same analysis for station 77 using unhomogenized (original) and homogenized mean annual humidity data. For evaluating the improvements of the homogenized curve and the corresponding trend, the humidity WegenerNet regional mean is plotted, too. As it is shown, the application of the recommended correction at station 77's new humidity sensor brings as well the humidity curve itself as the magnitude of the annual-mean linear trend much closer to the WegenerNet regional mean. Again, the found linear trends itself are not significant in a climate logical sense. In addition, as the data quality is in generally bad between 2010 and 2014 (for station 77 the data quality is bad between January 2007 and August 2013, see Figure 5.9), annual mean values are significantly affected by the lower values of flagged data (see Table 5.4). Furthermore, the relatively early sensor change of station 77 is probably responsible for the higher magnitude of station 77's linear trend compared to the WegenerNet regional mean linear trend. For the corresponding seasonal linear trend analyses the reader may

[10] This verification checks are done for the most affected stations, which all lead to significantly improved results.

[11] The anomalies are calculated compared to the mean of the WegenerNet regional mean 2007–2016.

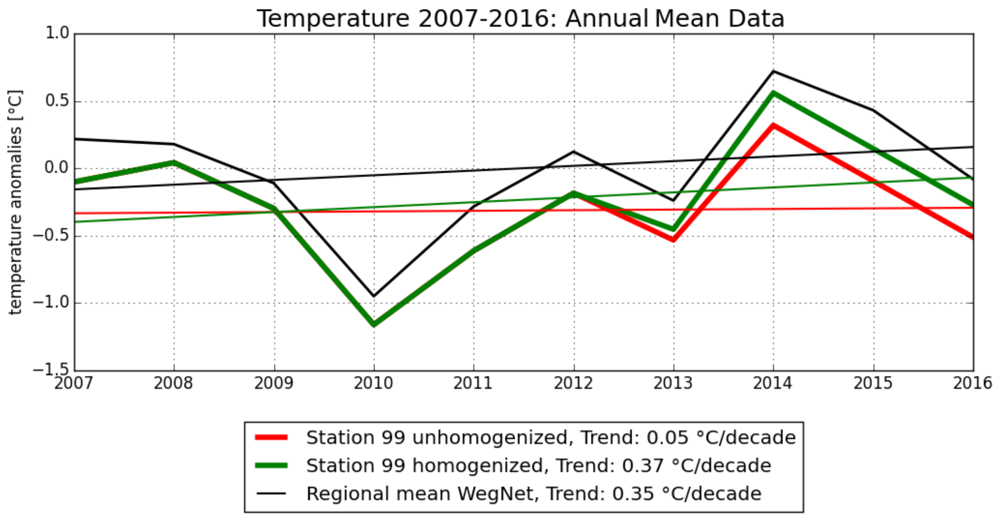


Figure 5.11.: Development of station 99's unhomogenized (original) and homogenized (by applying the recommended correction) annual-mean temperature anomalies and WegenerNet regional mean annual-mean temperature anomalies (compared to WegenerNet regional mean 2007–2016) with corresponding linear trends for 2007–2016.

have a look into Appendix A, Figure A.6.

5.4. Side Test: Applying the Method to Precipitation Data

To show the limits of the used method for analysing change points in the temperature and humidity data time series, this section presents the results for a side test of applying the same method on WegenerNet daily precipitation data. Therefore an analysis within all eleven primary stations including the reference station 77 is done. Due to their ability to measure liquid and solid precipitation, these stations are picked out for this test analysis.

For calculating the station's increment values, all available remaining stations are used as reference stations, similar to the humidity analysis. Again the increment is formed by subtracting the median daily precipitation of all reference stations from the candidate station's daily precipitation. Due to the fact of a large number of days without any precipitation in the WegenerNet, overall there exist many increment values with the magnitude of zero.

Figure 5.13 shows an example of station 77's complete analysis. The third panel in Figure 5.13 depicts the absolute daily precipitation amounts at station 77. It is shown that during summers, precipitation amounts reach higher values compared to winters, which causes that also the increment values (deviations) show their highest values during summers. At some days the increment magnitude amounts to ±30 mm and more, which are maybe indicators for heavy local precipitation events in the WegenerNet. So, with

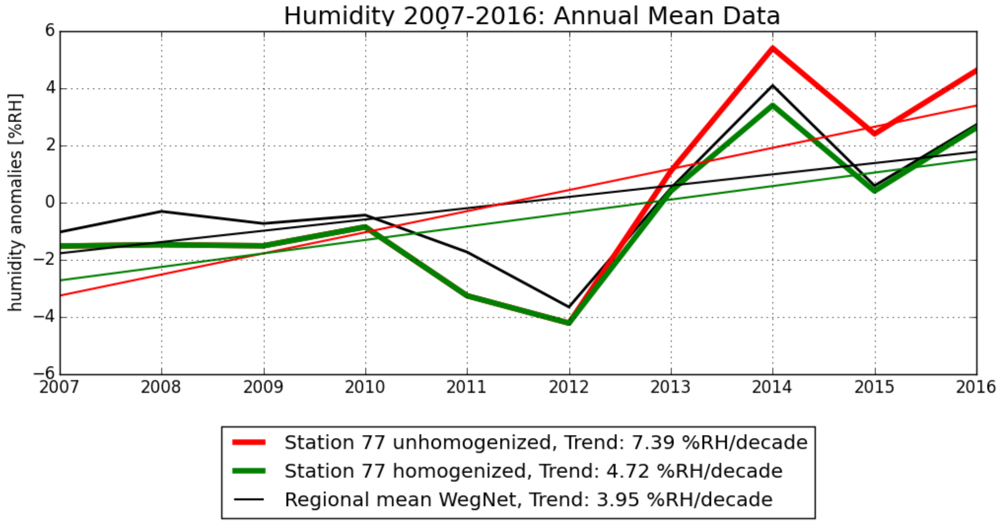


Figure 5.12.: Development of station 77's unhomogenized (original) and homogenized (by applying the recommended correction) annual-mean humidity anomalies and WegenerNet regional mean annual-mean humidity anomalies (compared to WegenerNet regional mean 2007–2016) with corresponding linear trends for 2007–2016.

the help of this special part of this first part of the method, it is possible to easily detect such mentioned exceptional cases. For a clearer understanding of the reasons of those, a more detailed research is required.

In contrast, the cumulative sum method is not able to determine correct change points. Even though a solution and even a change point is detected in Figure 5.13, its meaning and usefulness is low. That generally is the case due to the variability of rainy days. As shown, the increment mean for station 77 is 0.38 mm, which causes the effect that days without any rain (increment = 0) are added negatively to the cumulative sum of the increment. Finally this implies that periods of longer lasting rain or dryness strongly influence the cumulative sum calculation and therefore the determination of possible change points. Following from this, it is also impossible to calculate meaningful sensor deviations and therefore potential correction values for correcting possible inhomogeneities.

In conclusion, applying the used method on daily precipitation data allows to determine special exceptional cases with the help of the increment calculation. They possibly represent days of heavy precipitation events on a very local scale in the WegenerNet. However, it is impossible to determine inhomogeneities and also corresponding correct change points due to the randomly distributed rainy days in the data time series. This nicely illustrates the limits of the method, which is made for variables that provide a continuous time series.

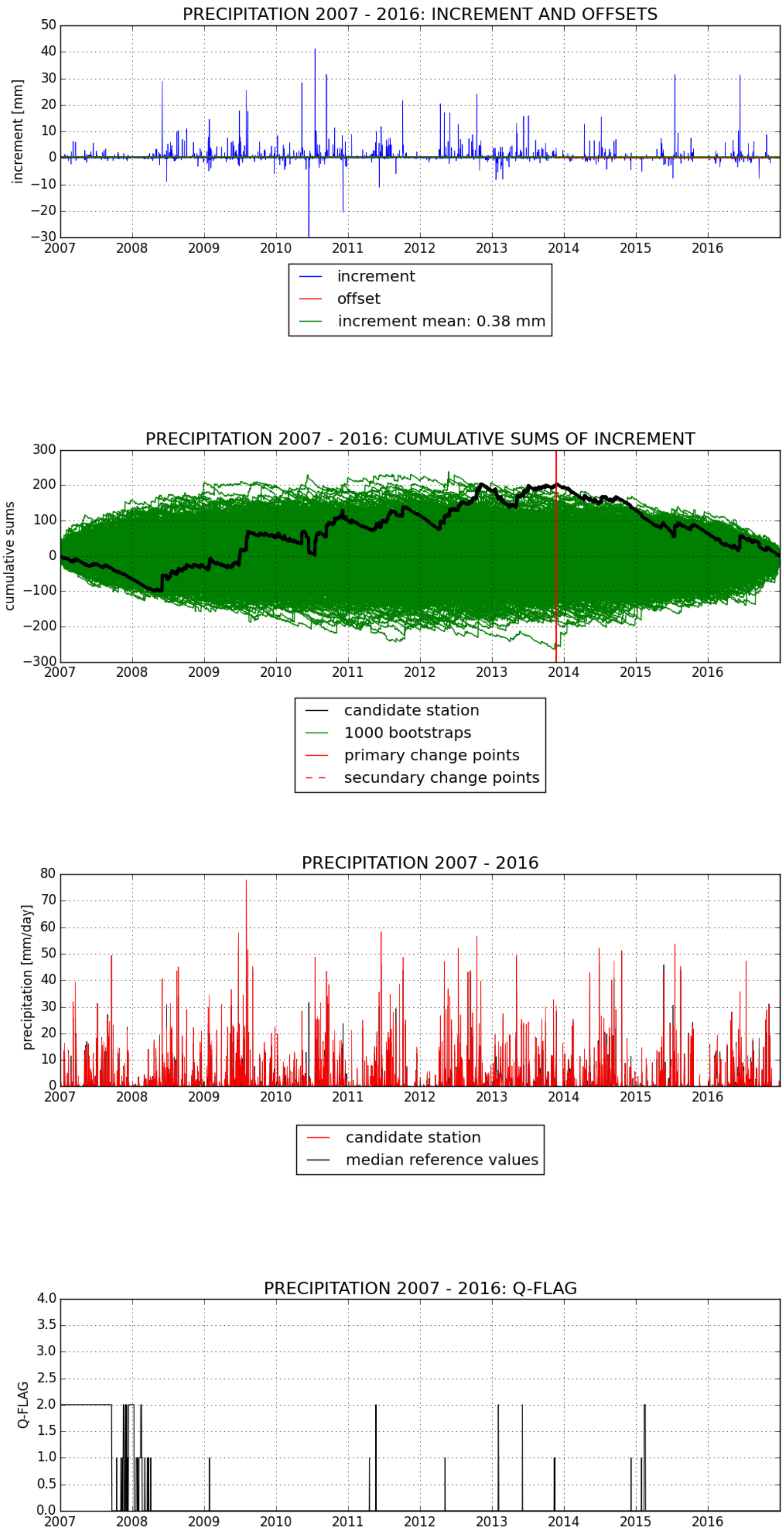


Figure 5.13.: Station 77: Test of the used method on precipitation data, using primary stations as reference.

6. Summary and Conclusions

The purpose of this Master thesis was to identify and eliminate inhomogeneities due to sensor changes in the daily temperature and humidity data of the WegenerNet Feldbach Region (FBR).[1] The aim was to ensure homogeneous data time series to prepare the data for climate trend studies. Beyond that, a quality evaluation of the data was done to find irregularities. The approach was to first find a method to analyse the data time series for natural and unnatural fluctuations by interstational comparisons. Afterwards, a change point detection was done to find possible inhomogeneities. Finally, correction values of identified inhomogeneities were provided.

After a basic overview of the WegenerNet FBR, the used temperature and humidity sensors and the WegenerNet Processing System (WPS), a short introduction to the weather and climate conditions was given. Then, a general description and visualization of the annual cycle of temperature and humidity in the FBR was done. After explaining the necessity of homogeneous data time series for applying them in climate trend studies, the used method of change point detection was explained, which is similar to a study done by Cowtan (2015). The target was to detect systematic (technical) change points with the help of a cumulative sum approach by Taylor (2000). Furthermore, the calculation of the finally recommended correction values was explained. Beyond that, individual local seasonal fluctuation effects were found at many stations, which made it more complicate to compute reliable correction values.

The results of the temperature analyses show that for 20 stations (13 % of all stations) a temperature correction due to the new installed sensors is necessary. Overall, 151 stations were observed, for 120 of them it was already possible to do a meaningful sensor comparison.[2] The recommended temperature correction values for those 20 stations go up to correction values of $|0.28|$ °C. Only if the sensor deviations exceeded a sensor uncertainty level of ± 0.100 °C, they were marked as potential inhomogeneity. If then the real sensor change date was supported by a detected unnatural change point, a correction of the sensor was recommended. Most of the 20 necessary corrections were positive, which means for the corresponding stations that the new sensors measure colder compared to their predecessors. Even though, there is no significant general warmer or colder measuring tendency of the newly installed TQ-sensors (only –0.02 °C mean difference).

Moreover, for some time ranges in the temperature time series, the data were interpolated by the WPS. As this system generates data for example out of the grid data (if there

[1] All temperature and humidity sensors (TQ-sensors) were changed between 2013 and 2016.

[2] For the rest (31 stations at which the sensor change does not reach enough time into the past), it will be possible to compute the values in the course of 2017, when the next sensor time series has grown sufficiently long.

is, e.g., no sensor installed for some weeks), the processing can lead to deviating temperature values during those time ranges. By an intrastational check, special correction values for those time ranges were generated, which also contribute to the improvements concerning the homogeneity of the temperature data time series. In concrete, eleven such necessary processing corrections are suggested. They range from magnitudes $|0.16|$ °C to $|0.69|$ °C and extend on average over three months of processed data. Furthermore, one defect temperature sensor at station 2 was detected, which was exchanged afterwards. A complete re-processing of the concerning time range is recommended.

By analysing relative seasonal fluctuations of different stations, an interesting positive winter temperature vertical gradient was found in the WegenerNet FBR. This means that the mean winter temperature over all available nine winters is increasing with the stations altitude. The linear regression over all 151 stations amounts to 1.48 °C per 100 m, and shows a significant positive correlation coefficient of 0.60, which is maybe due to days of strong inversion weather conditions during winters. In order to get a better understanding of this interesting phenomenon, further research in this field is required.

The results of the humidity analyses bring up necessary corrections at eleven stations (7 % of all stations). Again, 151 station were observed, but only for 104 stations it was possible to compute the homogeneity check. That is, on the one hand, again due to the too short time range of the newly installed sensors – similar to the temperature analysis – but on the other hand, it is due to the bad quality of the relative humidity data provided by the old TQ-sensors. This circumstance made it also necessary to somewhat adjust the used method of change point detection to get meaningful comparisons of the different sensors.

The recommended correction values of the necessary eleven corrections of the humidity sensors go up to $|3.4|$ %RH. Here, the minimum level of the sensor deviation to get the status of a potential inhomogeneity was to exceed the sensor uncertainty range of ±1.80 %RH. All recommended correction values are positive, with just one exception. That means that the affected new humidity sensors measure too dry, compared to the old ones. Overall, there exists a trend of drier measuring of the new humidity sensors, but it is again not significant (only –0.5 %RH) and therefore too small to justify a correction of all new humidity sensors by some constant positive correction value.

For station 18, a location change in 2015 caused remarkable changes as well in the temperature as in the humidity behaviour (the largest ones found in the network. This made it necessary to homogenize the old location of the station with respect to the conditions of the new location. In concrete, a correction of –1.09 °C and +5.2 %RH of the old location's data time series is needed.

Finally, a verification check – by some linear trend studies over the ten years of WegenerNet FBR data – showed that the data inhomogeneities could be effectively removed by applying the recommended correction values. Overall, a clear improvement of the temperature and humidity data could be achieved and the climate quality of the WegenerNet FBR is found overall very good.

A. Appendix

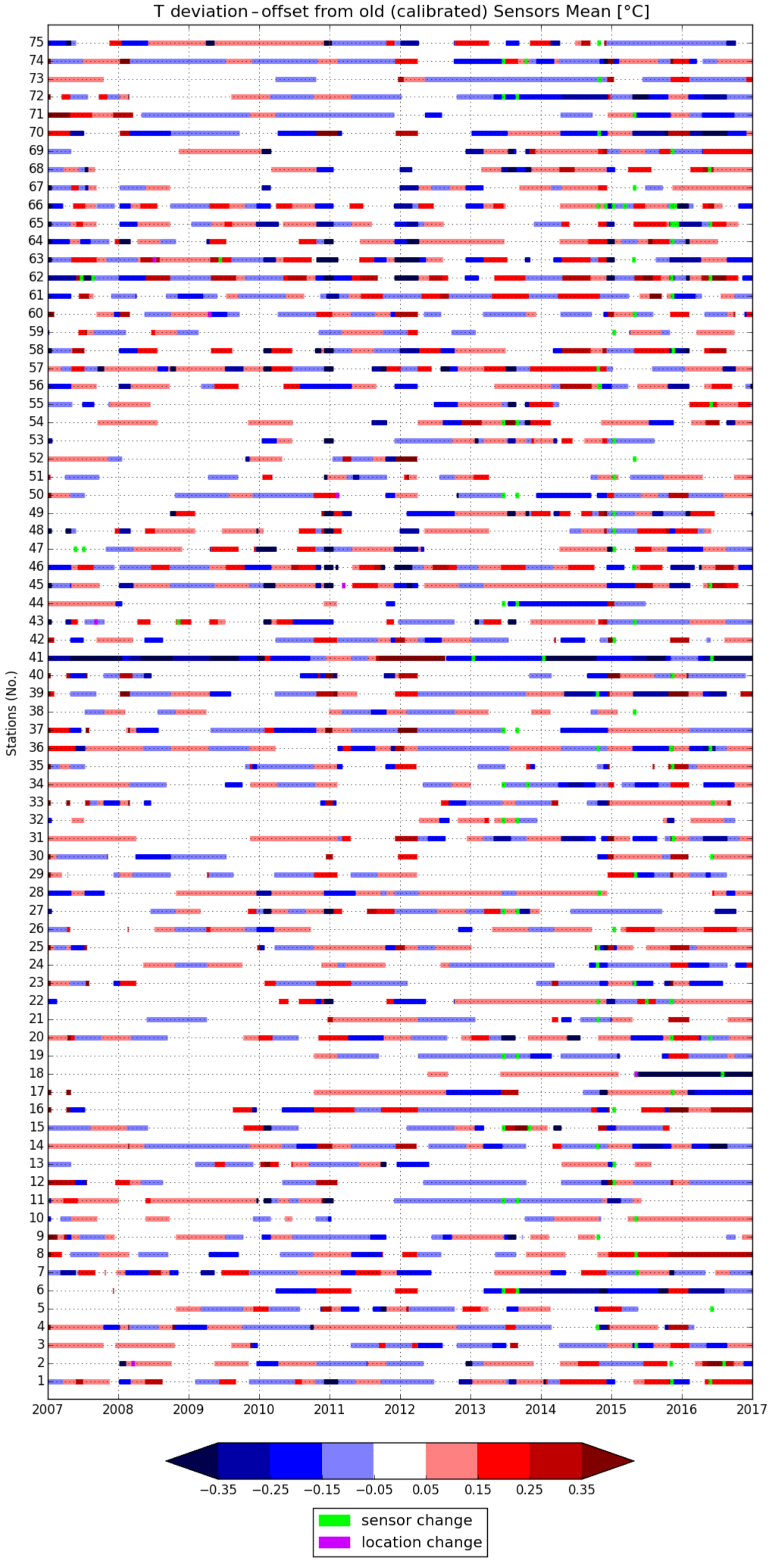


Figure A.1.: Temperature offset development for stations 1–75.

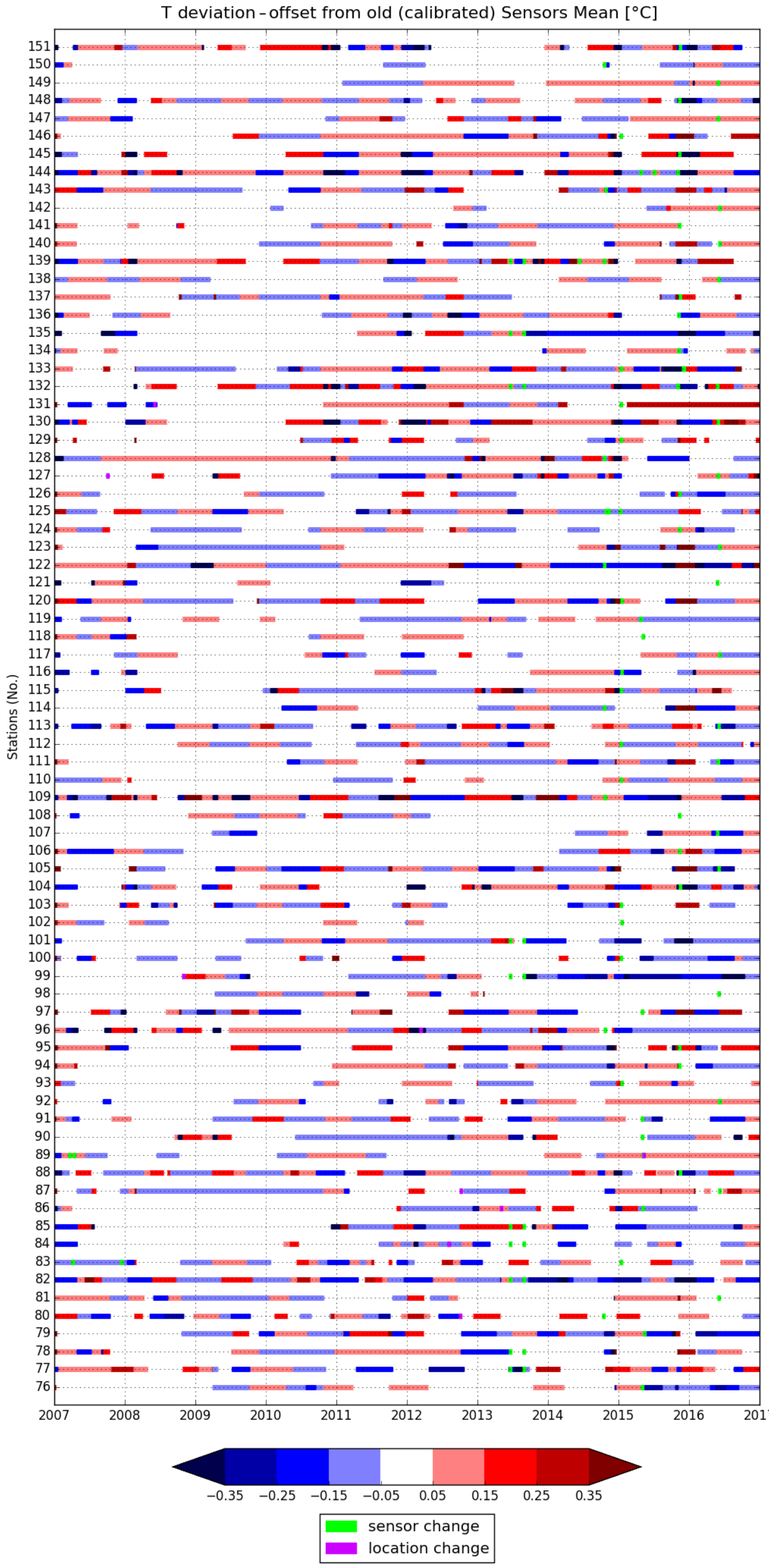


Figure A.2.: Temperature offset development for stations 76–151.

Table A.1.: Temperature: Theoretical Correction Values of new TQ-sensors for stations 1–76

Station ID	Date of Sensor Implementation	Theoretical Correction Value (°C)	Station ID	Date of Sensor Implementation	Theoretical Correction Value (°C)
1	2016-05-25	nan	39	2014-10-17	–0.01
2	2015-11-05	–0.21	40	2015-11-12	–0.01
3	2015-05-06	–0.02	41	2016-06-01	nan
4	2014-10-20	–0.06	42	2015-01-14	–0.09
5	2016-06-01	nan	43	2015-04-30	0.04
6	2013-08-29	0.23	44	2013-08-29	0.08
7	2015-05-12	0.03	45	2016-05-27	nan
8	2015-05-06	–0.28	46	2015-04-27	0.03
9	2014-10-21	0.00	47	2015-01-12	–0.04
10	2015-05-06	–0.08	48	2015-01-13	–0.11
11	2013-08-30	0.01	49	2015-01-13	0.08
12	2015-01-12	–0.03	50	2013-08-29	0.03
13	2015-01-12	–0.01	51	2015-01-15	–0.02
14	2014-10-20	0.15	52	2015-04-29	0.05
15	2013-10-29	0.03	53	2015-01-14	0.07
16	2015-01-14	–0.19	54	2013-08-30	–0.05
17	2015-11-10	0.10	55	2016-05-30	nan
18	2015-05-06	1.09	56	2014-10-27	0.00
19	2013-08-29	0.09	57	2014-10-21	0.01
20	2016-05-25	nan	58	2015-11-17	–0.05
21	2014-10-23	–0.08	59	2015-01-13	–0.02
22	2015-11-04	–0.05	60	2015-04-29	–0.03
23	2015-04-29	0.06	61	2015-11-10	0.05
24	2014-10-17	0.09	62	2016-05-25	nan
25	2014-10-21	–0.09	63	2015-04-27	0.17
26	2015-01-15	–0.13	64	2015-11-13	–0.03
27	2013-06-19	0.07	65	2016-05-27	nan
28	2014-10-28	–0.04	66	2015-11-24	0.01
29	2015-05-05	0.03	67	2015-04-30	–0.03
30	2016-06-03	nan	68	2016-05-23	nan
31	2015-11-16	0.08	69	2015-11-10	–0.07
32	2013-08-30	0.04	70	2014-10-27	0.17
33	2016-06-07	nan	71	2015-04-30	0.11
34	2013-10-23	0.08	72	2013-08-30	0.19
35	2015-11-13	–0.14	73	2014-10-28	–0.01
36	2016-05-27	nan	74	2013-10-15	–0.01
37	2013-08-29	0.03	75	2014-10-28	0.13
38	2015-04-28	0.00	76	2015-05-04	0.15

Table A.2.: Temperature: Theoretical Correction Values of new TQ-sensors for stations 77–151

Station ID	Date of Sensor Implementation	Theoretical Correction Value (°C)	Station ID	Date of Sensor Implementation	Theoretical Correction Value (°C)
77	2013-08-29	–0.08	115	2015-01-12	0.05
78	2013-08-30	–0.04	116	2015-01-16	0.04
79	2015-05-13	0.14	117	2016-06-06	nan
80	2014-10-16	–0.05	118	2015-05-06	0.04
81	2016-06-02	nan	119	2015-04-27	0.09
82	2013-08-29	0.18	120	2015-01-16	–0.11
83	2015-01-15	–0.07	121	2016-05-27	nan
84	2013-08-29	0.04	122	2014-10-19	0.12
85	2013-08-30	0.08	123	2016-06-07	nan
86	2015-05-06	0.10	124	2015-11-12	0.06
87	2016-06-07	nan	125	2014-10-27	0.02
88	2015-11-17	0.04	126	2015-11-11	0.13
89	2015-05-06	–0.06	127	2016-05-31	nan
90	2015-05-04	0.05	128	2014-10-18	0.05
91	2015-05-05	0.06	129	2015-01-14	–0.06
92	2016-06-06	nan	130	2016-05-30	nan
93	2015-01-16	–0.02	131	2015-01-13	–0.24
94	2015-11-11	0.07	132	2016-05-27	nan
95	2015-11-11	–0.08	133	2015-01-14	0.18
96	2014-10-22	0.09	134	2015-11-09	–0.01
97	2015-05-05	–0.05	135	2013-08-29	0.23
98	2016-06-02	nan	136	2015-11-09	0.03
99	2013-08-29	0.24	137	2015-11-16	–0.06
100	2015-01-12	0.10	138	2016-06-03	nan
101	2013-08-30	0.13	139	2014-10-18	–0.10
102	2015-01-16	0.00	140	2016-06-06	nan
103	2015-01-15	–0.08	141	2015-11-11	0.00
104	2015-11-16	0.11	142	2016-06-06	nan
105	2016-06-01	nan	143	2014-10-27	–0.02
106	2015-11-12	0.00	144	2015-11-04	0.15
107	2016-05-27	nan	145	2015-11-13	–0.01
108	2015-11-13	0.02	146	2015-01-13	–0.16
109	2014-10-22	0.10	147	2016-05-31	nan
110	2015-01-13	0.01	148	2015-11-10	0.11
111	2016-05-31	nan	149	2016-05-31	nan
112	2015-01-13	0.03	150	2014-10-20	0.05
113	2016-06-02	nan	151	2015-11-16	0.06
114	2014-10-20	0.02			

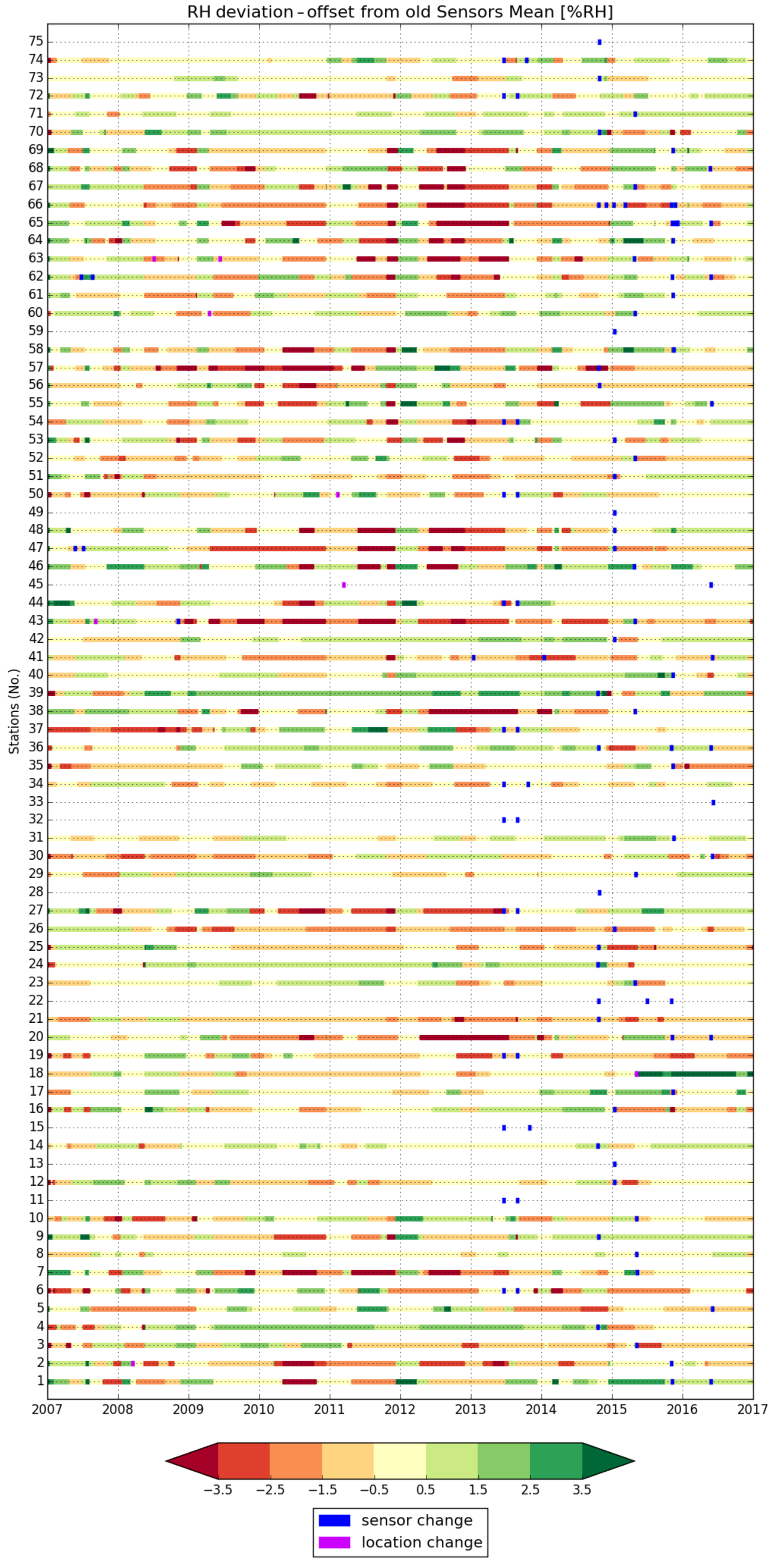


Figure A.3.: Humidity offset development for stations 1–75.

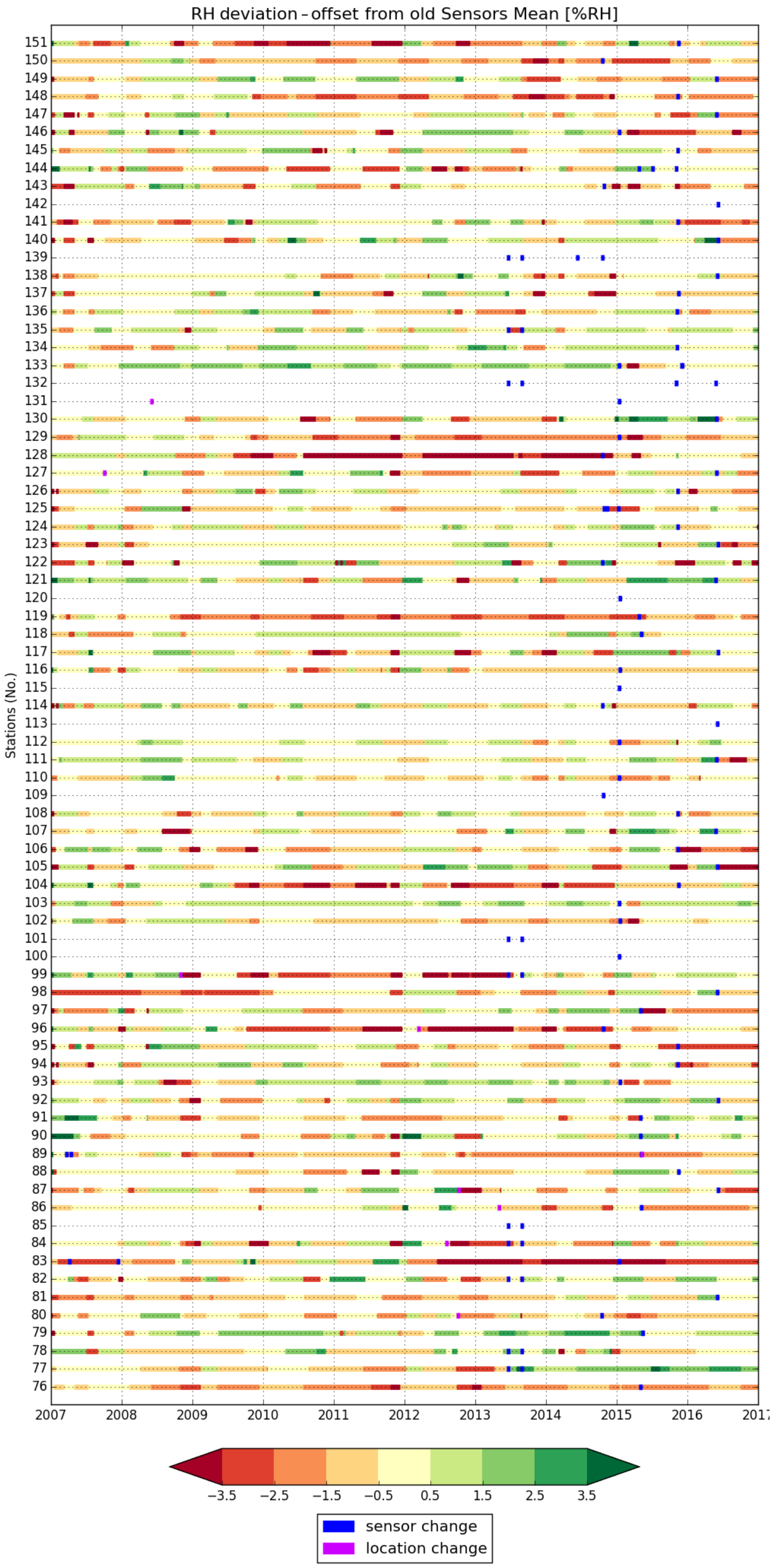


Figure A.4.: Humidity offset development for stations 76–151.

Table A.3.: Humidity: Theoretical Correction Values of new TQ-sensors for stations 1–76

Station ID	Date of Sensor Implementation	Theoretical Correction Value (%RH)	Station ID	Date of Sensor Implementation	Theoretical Correction Value (%RH)
1	2016-05-25	nan	39	2014-10-17	–0.7
2	2015-11-05	0.3	40	2015-11-12	0.3
3	2015-05-06	1.6	41	2016-06-01	nan
4	2014-10-20	0.6	42	2015-01-14	–0.2
5	2016-06-01	nan	43	2015-04-30	0.9
6	2013-08-29	1.0	44	2013-08-29	–0.4
7	2015-05-12	–0.1	45	2016-05-27	nan
8	2015-05-06	0.1	46	2015-04-27	–1.2
9	2014-10-21	–1.1	47	2015-01-12	1.4
10	2015-05-06	0.3	48	2015-01-13	–0.6
11	2013-08-30	nan	49	2015-01-13	nan
12	2015-01-12	0.4	50	2013-08-29	0.4
13	2015-01-12	nan	51	2015-01-15	–0.9
14	2014-10-20	–0.4	52	2015-04-29	0.8
15	2013-10-29	nan	53	2015-01-14	0.3
16	2015-01-14	1.2	54	2013-08-30	–0.4
17	2015-11-10	–0.7	55	2016-05-30	nan
18	2015-05-06	–5.2	56	2014-10-27	1.2
19	2013-08-29	1.3	57	2014-10-21	1.6
20	2016-05-25	nan	58	2015-11-17	–0.3
21	2014-10-23	1.6	59	2015-01-13	nan
22	2015-11-04	nan	60	2015-04-29	–0.4
23	2015-04-29	0.4	61	2015-11-10	–0.4
24	2014-10-17	0.3	62	2016-05-25	nan
25	2014-10-21	1.7	63	2015-04-27	0.1
26	2015-01-15	1.1	64	2015-11-13	0.1
27	2013-06-19	–0.9	65	2016-05-27	nan
28	2014-10-28	nan	66	2015-11-24	1.2
29	2015-05-05	–0.3	67	2015-04-30	0.7
30	2016-06-03	nan	68	2016-05-23	nan
31	2015-11-16	–0.8	69	2015-11-10	–0.2
32	2013-08-30	nan	70	2014-10-27	0.7
33	2016-06-07	nan	71	2015-04-30	–1.4
34	2013-10-23	0.1	72	2013-08-30	–0.2
35	2015-11-13	2.0	73	2014-10-28	0.1
36	2016-05-27	nan	74	2013-10-15	–0.7
37	2013-08-29	–0.1	75	2014-10-28	nan
38	2015-04-28	–0.2	76	2015-05-04	1.6

Table A.4.: Humidity: Theoretical Correction Values of new TQ-sensors for stations 77–151

Station ID	**Date of Sensor Implementation**	**Theoretical Correction Value (%RH)**	**Station ID**	**Date of Sensor Implementation**	**Theoretical Correction Value (%RH)**
77	2013-08-29	–2.0	115	2015-01-12	nan
78	2013-08-30	0.2	116	2015-01-16	0.7
79	2015-05-13	–0.4	117	2016-06-06	nan
80	2014-10-16	1.5	118	2015-05-06	–0.1
81	2016-06-02	nan	119	2015-04-27	1.6
82	2013-08-29	–0.6	120	2015-01-16	nan
83	2015-01-15	3.4	121	2016-05-27	nan
84	2013-08-29	0.4	122	2014-10-19	0.8
85	2013-08-30	nan	123	2016-06-07	nan
86	2015-05-06	2.0	124	2015-11-12	0.6
87	2016-06-07	nan	125	2014-10-27	1.0
88	2015-11-17	0.2	126	2015-11-11	1.2
89	2015-05-06	1.6	127	2016-05-31	nan
90	2015-05-04	–0.8	128	2014-10-18	0.7
91	2015-05-05	–0.8	129	2015-01-14	1.9
92	2016-06-06	nan	130	2016-05-30	nan
93	2015-01-16	0.7	131	2015-01-13	nan
94	2015-11-11	1.7	132	2016-05-27	nan
95	2015-11-11	2.6	133	2015-01-14	1.0
96	2014-10-22	0.8	134	2015-11-09	0.0
97	2015-05-05	2.3	135	2013-08-29	–0.4
98	2016-06-02	nan	136	2015-11-09	0.8
99	2013-08-29	–0.1	137	2015-11-16	1.4
100	2015-01-12	nan	138	2016-06-03	nan
101	2013-08-30	nan	139	2014-10-18	nan
102	2015-01-16	0.7	140	2016-06-06	nan
103	2015-01-15	–0.7	141	2015-11-11	2.6
104	2015-11-16	0.3	142	2016-06-06	nan
105	2016-06-01	nan	143	2014-10-27	1.7
106	2015-11-12	2.5	144	2015-11-04	–0.4
107	2016-05-27	nan	145	2015-11-13	0.7
108	2015-11-13	1.3	146	2015-01-13	2.3
109	2014-10-22	nan	147	2016-05-31	nan
110	2015-01-13	0.8	148	2015-11-10	1.7
111	2016-05-31	nan	149	2016-05-31	nan
112	2015-01-13	0.3	150	2014-10-20	1.8
113	2016-06-02	nan	151	2015-11-16	0.1
114	2014-10-20	0.5			

Table A.5.: Temperature: Seasonal Coefficients

Station ID	**Seasonal Coef. [°C]**	**Station ID**	**Seasonal Coef. [°C]**	**Station ID**	**Seasonal Coef. [°C]**	**Station ID**	**Seasonal Coef. [°C]**
1	0.14	39	–0.21	77	–0.15	115	0.07
2	0.15	40	–0.09	78	0.05	116	0.05
3	–0.05	41	–0.15	79	0.08	117	0.06
4	0.07	42	–0.13	80	–0.19	118	–0.04
5	–0.15	43	0.02	81	–0.05	119	–0.07
6	–0.07	44	–0.05	82	0.23	120	–0.12
7	0.10	45	0.24	83	0.14	121	0.02
8	–0.15	46	0.28	84	0.03	122	0.04
9	–0.07	47	0.20	85	–0.06	123	0.01
10	0.05	48	0.04	86	–0.04	124	–0.04
11	0.09	49	0.00	87	–0.02	125	–0.20
12	–0.14	50	–0.02	88	0.19	126	–0.05
13	0.03	51	–0.12	89	–0.05	127	0.01
14	–0.14	52	–0.11	90	–0.08	128	–0.05
15	–0.05	53	0.06	91	–0.17	129	–0.04
16	–0.09	54	–0.12	92	–0.06	130	0.31
17	0.06	55	–0.07	93	–0.03	131	–0.02
18	0.01	56	0.17	94	0.05	132	0.23
19	–0.03	57	–0.07	95	0.10	133	–0.04
20	–0.20	58	0.17	96	–0.08	134	0.00
21	–0.02	59	0.09	97	0.17	135	0.11
22	0.07	60	–0.13	98	–0.10	136	0.11
23	–0.08	61	0.21	99	–0.10	137	0.00
24	0.08	62	0.33	100	–0.05	138	0.09
25	–0.01	63	0.26	101	0.09	139	0.13
26	0.13	64	0.11	102	–0.09	140	–0.01
27	–0.01	65	0.17	103	–0.11	141	–0.01
28	0.06	66	0.19	104	0.11	142	0.03
29	–0.11	67	0.07	105	–0.13	143	–0.13
30	–0.07	68	0.04	106	–0.18	144	0.21
31	–0.18	69	0.04	107	–0.12	145	0.17
32	–0.04	70	–0.17	108	–0.04	146	0.06
33	0.01	71	–0.10	109	–0.23	147	0.08
34	–0.17	72	–0.04	110	–0.05	148	0.18
35	–0.01	73	–0.04	111	–0.10	149	–0.02
36	–0.16	74	0.00	112	–0.12	150	0.01
37	–0.13	75	–0.03	113	–0.18	151	0.13
38	–0.08	76	–0.11	114	–0.09		

Table A.6.: Humidity: Seasonal Coefficients

Station ID	**Seasonal Coef. [%RH]**	**Station ID**	**Seasonal Coef. [%RH]**	**Station ID**	**Seasonal Coef. [%RH]**	**Station ID**	**Seasonal Coef. [%RH]**
1	–0.93	39	0.64	77	0.21	115	–0.27
2	–0.89	40	0.07	78	0.38	116	–0.31
3	–0.13	41	0.20	79	0.34	117	0.66
4	0.14	42	–0.08	80	0.86	118	0.50
5	0.89	43	–0.95	81	0.38	119	0.70
6	0.61	44	–1.19	82	–0.35	120	–0.20
7	–1.50	45	–1.20	83	–0.41	121	–0.34
8	0.47	46	–2.33	84	0.60	122	0.37
9	–0.61	47	–0.92	85	0.33	123	0.23
10	–0.60	48	–0.85	86	–0.01	124	0.51
11	–1.15	49	–0.54	87	1.12	125	0.96
12	0.60	50	1.42	88	–0.24	126	1.16
13	–0.01	51	0.72	89	0.07	127	0.73
14	–0.12	52	0.75	90	–0.22	128	0.63
15	–1.25	53	–0.48	91	0.65	129	0.53
16	0.08	54	0.73	92	0.21	130	–0.67
17	0.47	55	0.13	93	0.14	131	0.51
18	0.77	56	–0.46	94	0.92	132	–0.24
19	1.02	57	0.21	95	0.43	133	0.25
20	0.04	58	–0.81	96	–0.24	134	–0.47
21	0.09	59	0.64	97	0.15	135	0.56
22	–0.57	60	–0.04	98	0.10	136	0.15
23	0.40	61	–0.49	99	0.59	137	0.07
24	0.34	62	–0.86	100	0.49	138	0.52
25	0.58	63	–1.55	101	–0.55	139	0.39
26	0.09	64	0.25	102	0.76	140	0.57
27	–0.11	65	–1.15	103	0.72	141	0.36
28	–0.77	66	–0.69	104	–0.55	142	0.27
29	–0.15	67	–1.10	105	1.24	143	0.47
30	0.67	68	–0.20	106	0.45	144	–1.35
31	–0.10	69	–0.66	107	0.40	145	–0.58
32	0.65	70	0.72	108	0.10	146	–0.05
33	0.35	71	0.50	109	–0.17	147	0.46
34	0.73	72	–0.14	110	0.92	148	0.69
35	0.58	73	0.28	111	0.88	149	1.06
36	0.22	74	0.74	112	0.71	150	0.78
37	1.70	75	–0.78	113	0.28	151	–0.51
38	–0.24	76	0.31	114	1.21		

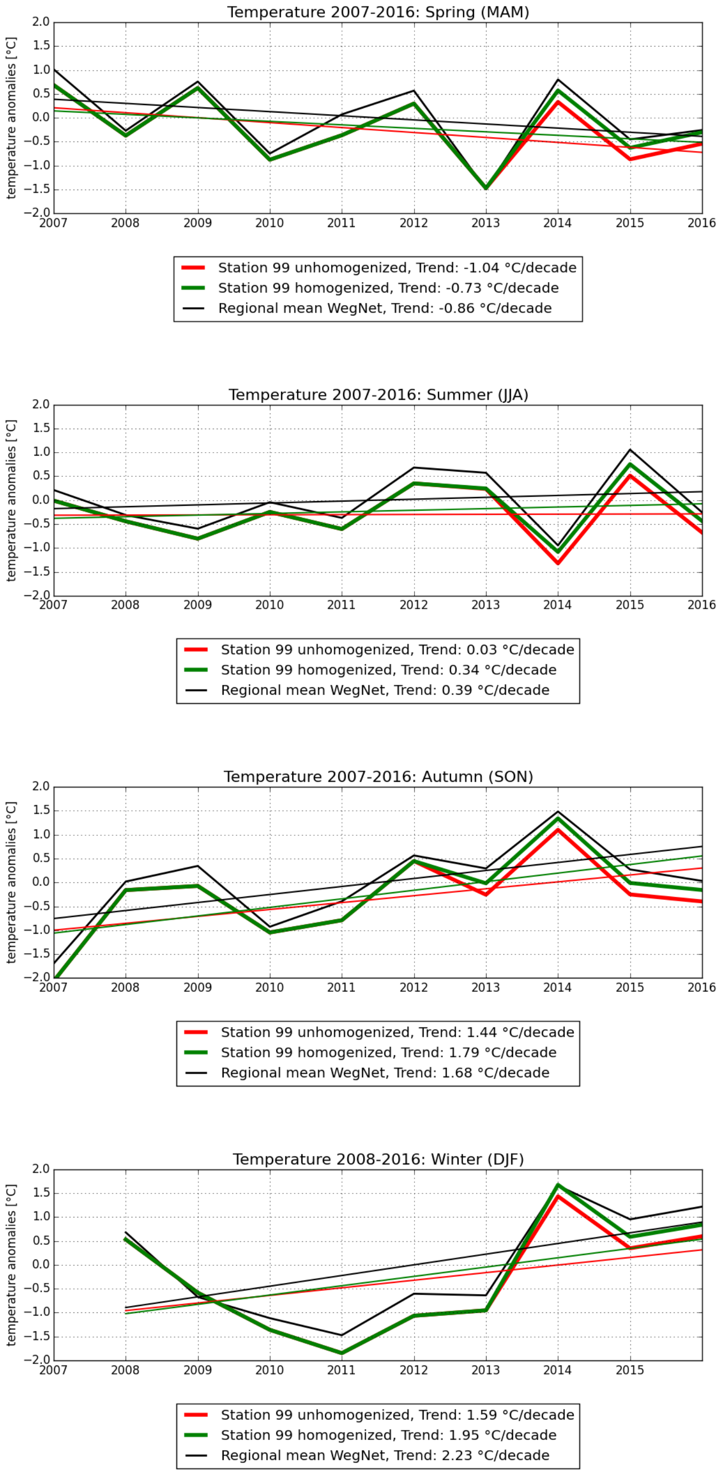


Figure A.5.: Development of Station 99's unhomogenized (original) and homogenized (by applying the recommended correction) seasonal temperature anomalies, and WegenerNet regional mean seasonal temperature anomalies (compared to WegenerNet regional mean 2007–2016) with corresponding linear trends for 2007–2016 for all different seasons.

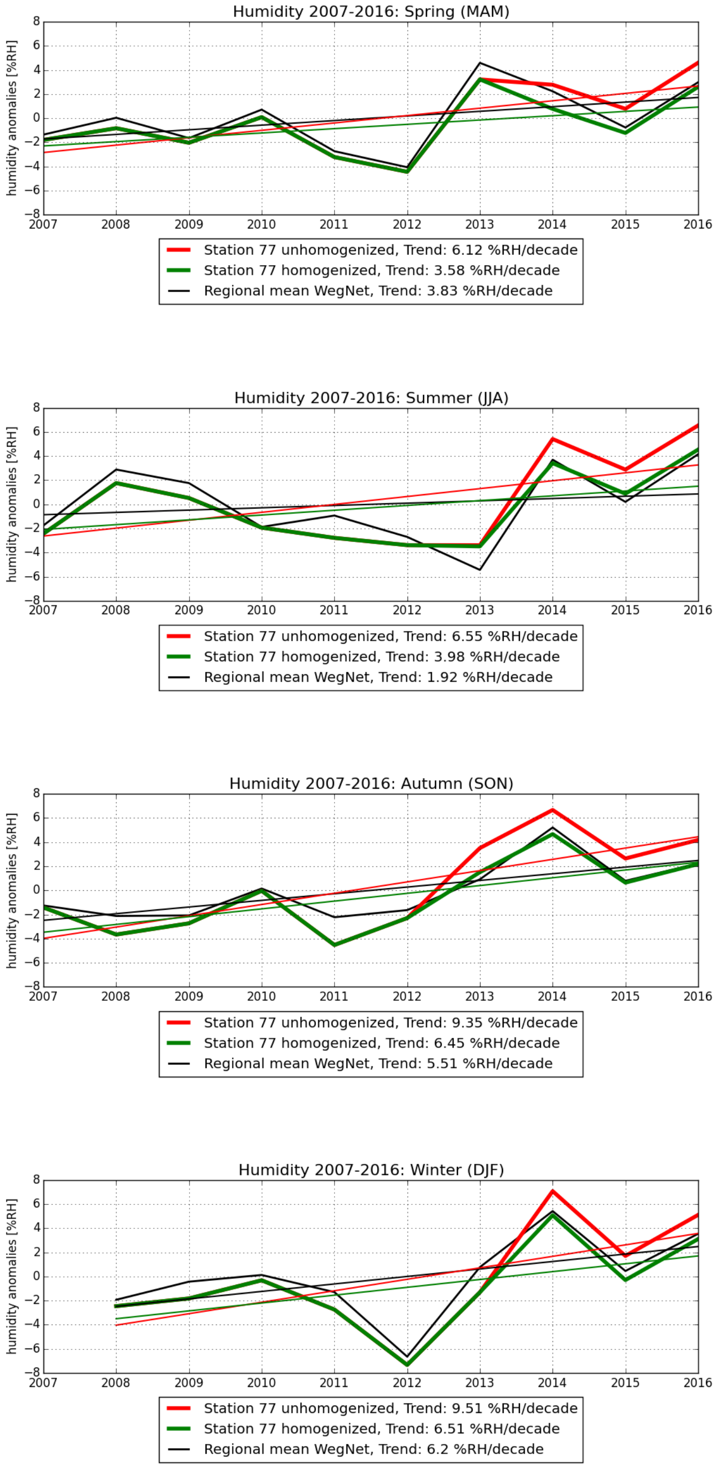


Figure A.6.: Development of Station 77's unhomogenized (original) and homogenized (by applying the recommended correction) annual humidity anomalies, and WegenerNet regional mean annual humidity anomalies (compared to WegenerNet regional mean 2007–2016) with corresponding linear trends for 2007–2016 for all different seasons.

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Abstract:
The WegenerNet Feldbach Region climate station network is a pioneering long-term high-resolution climate research facility in the southeast of the state of Styria in Austria. It covers an area of about 22 x 16 km^2 and contains more than 150 measurement stations, which have been operating and providing meteorological data since the beginning of 2007.
In order to meet the WegenerNet's objective of building up long-term climate observations at a very high resolution, it is necessary to base them on homogeneous data time series. As a complete change of temperature and humidity sensors took place between 2013 and 2016, this Master thesis identifies possible inhomogeneities in the temperature and humidity data time series, especially due to the sensor changes.
By using inter-stational comparisons, the evaluation tries to detect unnatural change points. A cumulative sum approach is applied on daily temperature and humidity data, an approach already applied recently in 2015 to global scale annual temperature data time series. As a result, temperature and humidity correction values for deviating newly installed sensors are recommended if a detected unnatural change point matches the real date of the sensor change and if sensor uncertainty thresholds of ±0.1°C (temperature) and ±1.8%RH (humidity) are exceeded by the discontinuity from the sensor change.
At about 14% of all stations, small but significant temperature sensor-change inhomogeneities >|0.1|°C were found. Likewise, significant humidity sensor-change inhomogeneities >|1.8|%RH were found at about 7% of all stations. These are corrected for in a new re-processing of the WegenerNet data.
Overall the evaluation, including stability checks for linear 10-year trends, confirms high and long-term stable data quality, in particular for temperature.

Zum Inhalt:
Das Klimastationsnetz WegenerNet Feldbachregion ist ein langfristiges, hochauflösendes Pionierexperiment für die Klimaforschung in der Südoststeiermark in Österreich. Es erstreckt sich über eine Fläche von ca. 22 x 16 km^2 und verfügt über mehr als 150 Messstationen, welche seit Beginn des Jahres 2007 in Betrieb sind und seither meteorologische Daten liefern.
Um die hohen Ansprüche des WegenerNet zu erfüllen, ist es notwendig für die zugehörige Klimaforschung homogene Datenzeitreihen zu verwenden. Da im Zeitraum zwischen 2013 und 2016 ein durchgehender Tausch der Temperatur- und Feuchtesensoren stattfand, beschäftigt sich diese Masterarbeit mit der Identifikation möglicher Inhomogenitäten in den Temperatur- und Feuchtedatenzeitreihen, speziell mit jenen, welche auf die Installation neuer Sensoren zurückzuführen sind.
Dazu wird eine Methode angewandt, die mit Hilfe von kumulierten Summen, basierend auf Tagesdaten von Temperatur und Feuchte, Wechselpunkte in den Zeitreihen sichtbar macht. Diese wurde bereits 2015 in anderem Kontext an globalen, jährlichen Temperaturdatenzeitreihen angewandt. Letztlich werden Korrekturwerte für die betroffenen neu installierten Sensoren vorgeschlagen, wenn ein gefundener Wechsel-Zeitpunkt mit dem wahren Datum des Sensortausches übereinstimmt und gleichzeitig die Unsicherheits-Bandbreite des Sensors von ±0.1°C (Temperatur) und ±1.8%RH (Feuchte) durch die Diskontinuität beim Wechsel überschritten wird.
Bei rund 14% aller Stationen wurde eine kleine aber signifikante Inhomogenität wegen des Temperatursensor-Wechsels gefunden. Gleichermaßen wurde bei rund 7% aller Stationen eine Inhomogenität wegen des Feuchtesensor-Wechsels entdeckt. Diese werden im Rahmen einer neuen Daten-Reprozessierung korrigiert.
Zusammenfassend wird anhand von Stabilitätschecks (z.B. 10-Jahres-Trends) bestätigt, dass sowohl eine hohe als auch langfristig stabile Datenqualität sichergestellt ist, speziell für die Temperatur.

Wegener Center for Climate and Global Change
University of Graz
Brandhofgasse 5
A-8010 Graz, Austria
www.wegcenter.at
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