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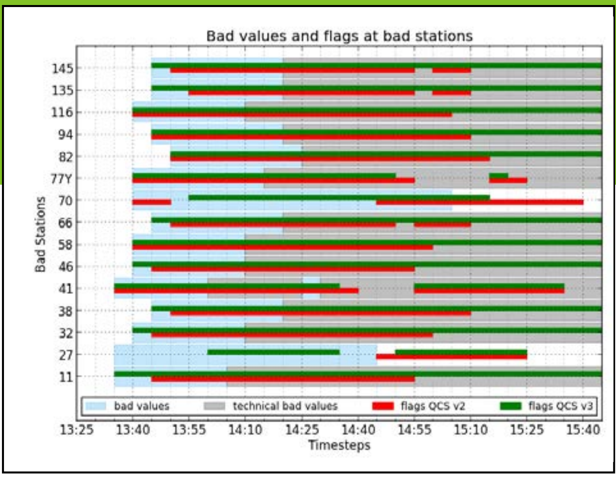

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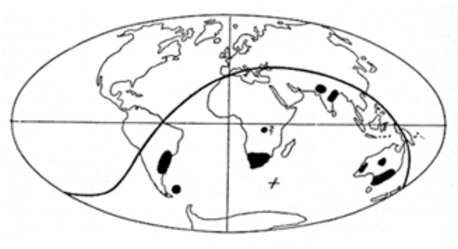
Improved Quality Control for the WegenerNet and Demonstration for Selected Weather Events and Climate

Daniel Scheidl

October 2014

The **Wegener Center for Climate and Global Change** combines as an interdisciplinary, internationally oriented research institute the competences of the University of Graz in the research area “Climate, Environmental and Global Change”. It brings together, in a dedicated building close to the University central campus, research teams and scientists from fields such as geo- and climate physics, meteorology, economics, geography, and regional sciences. At the same time close links exist and are further developed with many cooperation partners, both nationally and internationally. The research interests extend from monitoring, analysis, modeling and prediction of climate and environmental change via climate impact research to the analysis of the human dimensions of these changes, i.e., the role of humans in causing and being effected by climate and environmental change as well as in adaptation and mitigation. (more information at www.wegcenter.at)

The present report is the result of a Master thesis work completed in May 2014. The work was funded by a MSc thesis scholarship provided by the Wegener Center.



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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Master Thesis
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Improved Quality Control for the WegenerNet and Demonstration for Selected Weather Events and Climate

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Abstract

The WegenerNet is a network of 151 meteorological stations covering an area of about 20×15 km in the south-east of Austria and providing near real time data with a resolution of five minutes. The data quality is ensured by a variety of procedures and checks, which are subsumed and automated in the Quality Control System (QCS).

The objective of this thesis was to evaluate and improve the QCS with focus on precipitation data. Also a brief introduction to the WegenerNet and the QCS is given.

The evaluation included a statistical analysis backing the focus on precipitation, tests of the validity of several climatological thresholds and check parameters and an assessment of the performance of the QCS when confronted with typical rain gauge malfunctions and with snowfall events.

Main areas of improvement were revisions of the climatological thresholds for precipitation and relative humidity, the correction of some inadequate algorithms related to snowfall events and a redesign of the interstational comparison of precipitation data. The parameters of the existing interstational check were revised and four new interstational checks, each tailored to a specific rain gauge malfunction, were implemented. Furthermore, the processing speed of the QCS was sped up by about 40 %.

A verification of the improvements was done on the basis of five case studies. The results show a significantly increased number of detected bad values as well as a reduction of false alarms for three convective rainfall events of varying length and intensity. The handling of stratiform rainfall events had been already relatively good in the existing QCS version and a case study therefore did not show much change. A fifth case study confirmed the improved handling of snowfall events. Furthermore, an analysis of the seasonal precipitation sums in 2011 indicated a decreased underestimation of climatological precipitation sums.

Overall the QCS upgrades clearly benefited the data quality available to users.

Zusammenfassung

Das WegenerNet ist ein Netzwerk von 151 meteorologischen Stationen im Südosten Österreichs, das für ein Gebiet von etwa 20×15 km Messwerte mit einer zeitlichen Auflösung von fünf Minuten liefert. Die Datenqualität wird durch eine Reihe von Plausibilitätsprüfungen sichergestellt, welche im Quality Control System (QCS) zusammengefasst und automatisiert durchgeführt werden.

Das Ziel der vorliegenden Masterarbeit war die Evaluierung und Verbesserung des QCS, mit Schwerpunkt auf der Qualitätskontrolle von Niederschlagsdaten.

Die Evaluierung umfasste eine statistische Analyse der bisher als fehlerhaft markierten Daten, die Überprüfung einiger in den Plausibilitätsprüfungen verwendeter Parameter sowie eine Analyse der Leistungsfähigkeit des QCS bei Auftreten typischer Fehlfunktionen der Niederschlagsgeber und bei Schneefallereignissen.

Auf Basis der Ergebnisse wurde eine Reihe von Modifikationen am QCS durchgeführt. Insbesondere waren dies die Ausweitung klimatologischer Grenzwerte, die Korrektur einiger bei Schneefall inadäquater Algorithmen, die Überarbeitung des Interstations–Vergleichs von Niederschlagssummen, sowie die Einführung zusätzlicher Vergleichstests, die auf typische Fehlfunktionen der Niederschlagsgeber spezialisiert sind. Auch die Prozessierungsgeschwindigkeit des QCS wurde um ca. 40% gesteigert.

Die Verbesserung der Datenqualität wurde anhand von fünf Fallstudien überprüft. Für konvektiven Niederschlag zeigte sich eine erheblich verbesserte Detektion fehlerhafter Werte bei gleichzeitiger Abnahme von fälschlich als problematisch markierten Werten. Bei stratiformem Niederschlag war die Leistung des QCS schon vor den Modifikationen gut und es gab daher keine wesentlichen Änderungen. Die verbesserte Vorgangsweise bei Schneefall wurde bestätigt und eine Analyse der saisonalen Niederschlagssummen im Jahr 2011 deutete auf eine nun geringere Unterschätzung dieser Summen hin.

Insgesamt liefert das QCS nun eindeutig verbesserte Datenqualität an die NutzerInnen.

Acknowledgements

In the first place I want express my gratitude to my supervisor Prof. Gottfried Kirchengast for giving me the opportunity to write my master thesis at the Wegener Center for Climate and Global Change and for his encouragement and support. Not only did he spend many hours discussing subtle details of my work, but also fueled my enthusiasm in getting deeper and deeper into the topic.

I am deeply indebted to my co-supervisor DI Jürgen Fuchsberger for guiding me through the process of writing this thesis. Besides giving me continuous support and scientific advice, he also shared a large amount of IT-related knowledge with me for which I am very grateful.

In many discussions Christoph Bichler provided much needed information about typical malfunctions as well as valuable insights into many other interesting aspects of the WegenerNet. Advice given by Dr. Thomas Kabas has been very helpful in understanding and improving the algorithms. Also the exchange of data, findings and motivation with Katalin Szeberényi MSc. made work a lot easier. I want to thank all of you.

Furthermore, I want to thank my colleagues at the Wegener Center for creating such an inspirational and enjoyable working environment.

Finally, I wish to thank my family for their confidence and support.

Contents

1 Introduction

High-resolution weather and climate data from ground-based observation networks are required by a broad range of scientific fields. Obviously such data are needed for the study of meteorological processes on small scales, where weather radar and satellite data are not adequately available or not accurate enough. Prominent examples are local wind systems, convective processes and the spatial variability of rainfall (see e.g Krajewski et al. 2003; Mandapaka and Qin 2013). On the other hand the point measurements from ground-based networks are used to evaluate and adjust the inherently space-averaged measurements of weather radars (see e.g. Wang et al. 2013; Pedersen et al. 2010; Peleg et al. 2013) and satellite-based sensors (see e.g. Amitai et al. 2012; Yilmaz et al. 2005). Also regional climate models (Prein et al. 2013) and operational weather forecast models (Kann et al. 2011) can be evaluated.

In order to supply such data for scientific purposes as well as to satisfy the local public, private and commercial demand for weather and climate data, the WegenerNet was established in 2006 by the Wegener Center for Climate and Global Change (Kirchengast et al. 2014). Unlike most other high resolution observation networks, the WegenerNet is planned to be a long-term project. A similar project is the Walnut Gulch Experimental Watershed (85 rain gauges covering 149 km^2, temporal resolution 1 min, see Goodrich et al. 2008), but it is more focused on precipitation and hydrology.

During the last decades a large variety of quality control procedures have been developed to ensure the usability of ground-based meteorological observations. Hubbard et al. (2012) and Estévez et al. (2011) provide up-to-date surveys and assessments of many of those procedures. However, despite the intense research on quality control procedures, they still have to be tailored to the characteristic properties of the specific observation net and continuously improved.

The objective of this thesis is to identify weaknesses of the current Quality Control System (QCS) of the WegenerNet and to improve parts of concern. The focus is on precipitation data and in particular the interstational comparison of measurements. Methodically, this study relies to a large part on case studies and series of spatial plots.

The first chapter gives a basic introduction to the WegenerNet. First general information on the network design is provided (measured parameters, station types, spatial arrangement, data processing chain). Then an overview of the QCS and specifically to the various quality checks applied therein is given.

In chapter 2 the results of an evaluation of the QCS are presented. This evaluation consists of three parts: a statistical analysis of data that were flagged as defective, tests of the validity of several boundary values and check parameters and finally an assessment of the performance of the QCS when confronted with typical rain gauge malfunctions and snowfall events.

Subsequently the modifications that were done to the QCS in order to improve the weaknesses found are presented in chapter 3, comprising the modification of several boundary values and check algorithms, the introduction of a new concept for the interstational comparison and new checks, and the improvement of processing speed.

The actual improvement is demonstrated based on five case studies on the one hand, and on the basis of seasonal precipitation sums on the other hand, in chapter 4. Finally the conclusion chapter gives a brief summary and discusses possible further improvements.

Overall the QCS upgrades are found to clearly benefit the data quality available to users of the WegenerNet precipitation data.

2 The WegenerNet and its Data Quality Control

This chapter gives a basic introduction to the WegenerNet and an overview of the existing quality control procedures. Since the later chapters focus largely on the quality control of precipitation data, and in particular on the intra- and interstational checks, information related to these topics is stressed here as well. For a more detailed description of the WegenerNet, see Kirchengast et al. (2014) and Kabas (2012).

2.1 The WegenerNet Climate Station Network

The WegenerNet is a climate station network located in the south-east of Austria. It consists of 151 stations, covering an area of about 20 km × 15 km around the town of Feldbach. The parameters measured net-wide are air temperature, (liquid) precipitation and relative humidity. They are referred to as basic parameters. At some stations also solid precipitation (heated rain gauges), wind parameters (mean wind speed, mean wind direction, peak gust and peak gust direction), soil parameters (soil temperature, pF-value, soil moisture and soil electric conductivity), air pressure and net radiation are measured. The temporal resolution of all parameters is five minutes, except for some soil parameters, which have a temporal resolution of 30 minutes. The spatial arrangement of the WegenerNet stations is shown in Figure 2.1.

There are four types of stations in the WegenerNet:

1. The 127 *base stations*, measuring the basic parameters air temperature, relative humidity and precipitation. They are equipped with unheated rain gauges of the type Friedrichs.

2. The twelve *special base stations*, being a base station with additional sensors for the soil parameters. One of the special base stations does not measure precipitation.

3. The eleven *primary stations*, measuring air temperature, precipitation, relative humidity and the wind parameters. Unlike the base stations and the special base stations, the primary stations are equipped with heated rain gauges and therefore can measure solid precipitation as well. Until October 2013 rain gauges of the type Young were used, which were then replaced by rain gauges of the type Meteoservis (for details see Szeberenyi (2014) and Kabas (2012)).

Table 2.1: Specifications of the different rain gauge models used in the WegenerNet (adapted from Kabas 2012).

Model	**Collection Area**	**Resolution**	**Accuracy**	**Heating**
Friedrichs 7042	$211\,cm^2$	0.1 mm	$< 25\,mm\,h^{-1}$: $\pm 2\,\%$ $< 50\,mm\,h^{-1}$: $\pm 3\,\%$	no
Young 52202	$200\,cm^2$	0.1 mm	$< 25\,mm\,h^{-1}$: $\pm 1\,\%$ $< 50\,mm\,h^{-1}$: $\pm 3\,\%$	yes
Meteoservis (Kroneis) MR3H	$500\,cm^2$	0.1 mm	$< 30\,mm\,h^{-1}$: $< -2\,\%$ $< 100\,mm\,h^{-1}$: $< -10\,\%$ $< 200\,mm\,h^{-1}$: $< -15\,\%$	yes

4. The single *reference station*, measuring the air temperature, relative humidity, precipitation, the wind parameters, air pressure and net radiation. It is equipped with three rain gauges, of the types Friedrichs, Young and Meteoservis, to allow comparisons between the different rain gauge models.

The specifications of the three rain gauge models used at WegenerNet stations are shown in Table 2.1. An analysis of the systematic differences between the rain gauge types was recently done by Szeberenyi (2014).

The WegenerNet stations are arranged approximately on a grid with a spacing of $1.4\,km \times 1.4\,km$. The reference station is situated near the center of the WegenerNet area. While the locations of the special base stations on the grid were selected to cover all main soil types occurring in the WegenerNet area (Kabas 2012), the distribution of the primary stations is a compromise between a good areal coverage and a coverage of six *location classes*, which were defined according to the location of a station between valley floor and ridges of hills (see Table 2.2).

Table 2.2: Location classes of WegenerNet stations.

Location class
Valley floor
Foot of the slope
Lower slope
Middle slope
Upper slope
Ridge

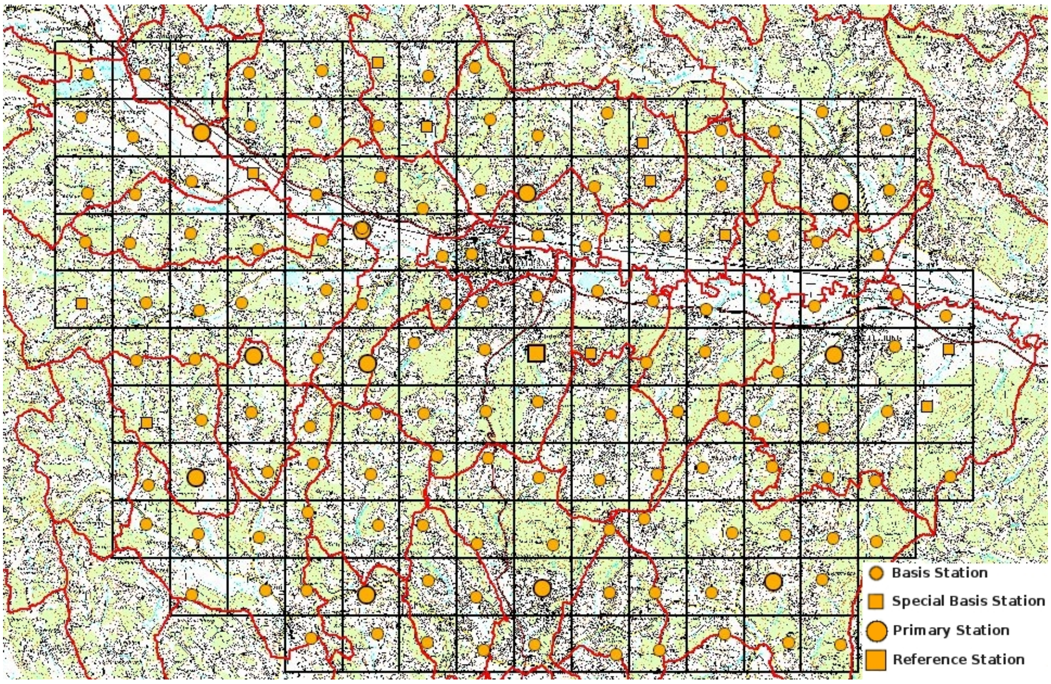

Figure 2.1: Spatial arrangement of the different station types in the WegenerNet.

In addition to the WegenerNet stations, there are also two weather stations of the Austrian meteorological service, Central Institute for Meteorology and Geodynamics (ZAMG), located within the WegenerNet area. Data from these stations, which are located near Feldbach and Bad Gleichenberg, are used by the quality control system of the WegenerNet in two ways. On the one hand data from these stations had been used to define several climatological boundary values that WegenerNet data are checked against. On the other hand WegenerNet data are also compared to the concurrent measurements of these ZAMG stations (see Section 2.2).

The landscape of the WegenerNet area is dominated by a typical form of hills, the so-called Riedels, and the up to 2 km wide valley of the Raab river (see Figure 2.1). According to Kabas (2012), the altitude of the Raab valley within the WegenerNet area is about 250 m to 300 m above sea level. The typical altitude of the Riedels is about 400 m above sea level and there are a few peaks, with altitudes up to 600 m above sea level. The station altitudes range between 257 m and 520 m, with a mean altitude of 331 m. For a climatological description of the region, see Wakonigg (1978) and Kabas (2012).

2.2 The Quality Control System of the WegenerNet

In this section an introduction to the WegenerNet data processing and in particular to the existing Quality Control System (QCS) is given. Several tables of boundary values related to the various checks performed by the QCS are not given here, but they are included in the Appendix for convenient readability.

After being measured at the individual stations, WegenerNet data run through several automated processing steps, which are subsumed under the WegenerNet Processing System (WPS). Every hour the measured data are transmitted to the Wegener Center servers via GPRS, where they are stored in a database as Level 0 data. This Level 0 data are then further processed to quality controlled Level 1 data by the QCS. In a subsequent processing step, the Level 1 data are used in the Data Product Generator (DPG) to interpolate to grid data and to generate data products of a different temporal resolution. If there are data missing, the DPG tries to close the gaps by temporal or spatial interpolation. Finally the resulting data products are stored as Level 2 data and can be accessed at the WegenerNet data portal (www.wegenernet.org).

The WPS was designed to do near-real time processing of the data. Incoming data are checked by the QCS every hour and data products are available on the data portal within at most one and a half hour after their measurement. Since the ZAMG data, which are used for an external reference check, are available only with a delay of one day the WegenerNet data are reprocessed after two days. This also allows to process WegenerNet data that were for some reason not transmitted in real time. For a more detailed description of the WPS see Kirchengast et al. (2014) or Kabas (2012).

The main purpose of the QCS is to check the technical and physical plausibility of the data values. Besides that, it also checks the availability and creates fail ("-9999") values for times of missing data. This is done by applying a variety of checks on each Level 0 data value, which are categorized into eight Quality Control Layers (QC-layers). The specific checks of each layer are also referred to as *rules*. A detailed list of all rules is given in Table 1 in the Appendix.

The information whether a data value has passed or failed the checks of a specific QC-layer is stored in a Quality Flag (QF). If a data value fails a check of layer n, the value of 2^n is added to the QF. Therefore QF 0 denotes a data value that did not fail any checks, while e. g. QF 96 denotes a data value that failed checks both in the layers 5 and 6. Analogously a no_ref flag is set, if a check could not be done, e. g. due to missing reference data from neighbor stations. Only data values with QF 0, and in case of precipitation also no_ref flag 0, are used in the DPG.

QC-layer 0 – Operations check: The original intention of this layer was to manually flag data in case of a station breakdown (e. g. maintenance, sensor out of order,...). Data flagged in layer 0 were supposed to have their value set to "-9999" by the QCS and skip all other layers. However, this layer was never fully implemented in the QCS as it was not fully needed.

QC-layer 1 – Availability check: Layer 1 checks whether the Level 0 data for the tested time interval are available in the database. If there are no data available, a Level 1 database entry is created with a data value of -9999 and a layer 1 quality flag set.

QC-layer 2 – Sensor check: In layer 2 it is checked whether a data value is within the technical min-/max-specifications of the respective sensor. If the data value is lower (rule 0) or higher (rule 1) than the corresponding boundary value, a layer 2 quality flag is set. For precipitation the sum of the last five minutes is checked. If the sum can not be build, e. g. due to missing data, a no_ref flag is set. All boundary values are technical sensor specifications provided by the manufacturer of the respective sensor except, for the boundary values of the precipitation sensors. Their lower boundary value is obviously zero, while the upper boundary value is the empirically derived maximum number of tips per time period. The layer 2 boundary values are given in Table 2 and Table 3 in the Appendix.

QC-layer 3 – Climatological check: In layer 3 it is checked whether a data value is within a reasonable climatological range. Again rule 0 checks the lower boundary and rule 1 checks the upper boundary. Monthly climatological boundary values were produced using long-time data from ZAMG stations in the region. Wind direction and peak gust direction are not checked because their short-term behavior can not be reasonably compared to climatological values. For technical reasons, the maximum allowed precipitation rate is not checked in layer 3, but in layer 4. The layer 3 boundary values are given in Table 4 in the Appendix.

QC-layer 4 – Time variability check: Layer 4 checks the data for implausibly fast changes and implausibly long times of constancy. To detect too fast changes, the five minute gradients of the parameters relative humidity, precipitation, soil temperature, pF-value, air pressure and net radiation are compared to monthly lower (rule 0) and upper (rule 1) boundary values derived from ZAMG data. The boundaries of net radiation are different for nighttime and daytime measurements. Day is defined as the time from two hours before sunrise to two hours after sunset.

Implausible constancy is checked for the parameters air temperature, relative humidity, wind speed, wind direction, peak gust, peak gust direction, air pressure and radiation in rule 2. The standard deviation of the measurements within the last hour (the last three hours for air pressure and for humidity $> 80\,\%$) is compared to a very small boundary value. For temperature and humidity this boundary value is $0.002\,\mathrm{K}$ and $0.02\,\%$, respectively. For all other checked parameters the boundary value is the resolution of the respective sensor. The boundary values of the time gradient check are given in Table 5 and Table 6 in the Appendix.

QC-layer 5 – Intrastational check: Layer 5 checks the coherence of several parameters measured at the same station. If the mean temperature of the last five hours at a station is below 2 °C, any precipitation measured by an unheated sensor at the respective station is flagged in rule 2. Also the precipitation measurements of the three different sensors at the reference station are compared to each other (rule 4). The wind parameters are checked for certain combinations of measured values, that indicate sensor failures, and the consistency of wind speed and peak gust are checked (rules 5-8). For example it is physically impossible that the wind speed, which is a temporal mean, is higher than the peak gust.

QC-layer 6 – Interstational check: In layer 6 the measurements are compared to the measurements of neighboring stations. This is only done for the parameters air temperature, relative humidity and precipitation, which are measured grid-wide. For temperature and humidity a data value must be within a certain range from the median of the data values of the neighboring stations in order to pass the check. There have to be at least four appropriate neighboring stations. The interstational check of precipitation compares the precipitation sum of the last hour with the respective sums of at least five neighboring stations. If all neighboring stations measured a precipitation sum of less than or equal to $0.13\,\mathrm{mm\,h^{-1}}$, the precipitation sum of the candidate station must not be greater than $1.0\,\mathrm{mm\,h^{-1}}$. On the other hand if at least one neighboring station measured more than $0.13\,\mathrm{mm\,h^{-1}}$, the precipitation sum of the candidate station must be within a certain range from the median of the neighbor values. While for temperature and humidity the allowed range from the median is a fixed value, the allowed range for precipitation is whichever is the largest of:

- $1.2 \times \min\left(\mathrm{median}\left(N\right) - \min\left(N\right), \max\left(N\right) - \mathrm{median}\left(N\right)\right)$
- $0.2 \times \mathrm{median}\left(N\right)$
- a fixed value of $1.0\,\mathrm{mm\,h^{-1}}$

with N being the 60 min precipitation sums of the neighboring stations.

Neighborhood of stations is defined upon topographic criteria. There are several levels of neighborhood (Table 2.3 and Table 2.4, see also Kabas (2012)) and the interstational check tries to use neighbors of a level as low as possible. Starting with all available level I neighbors, the neighbors of the next level are included as well, until the required number of neighbors is available. If all neighborhood levels are used, but there are still not enough neighbors available, a no_ref flag is set.

Table 2.3: Station neighborhood criteria for air temperature and relative humidity. The location classes are given in Table 2.2.

Neighborhood level	Distance	Location Class	Difference in Altitude
I	< 2.5 km	same	< 75 m
II	< 5.0 km	same	< 75 m
III	< 2.5 km	adjacent	< 75 m
IV	< 5.0 km	adjacent	< 75 m

Table 2.4: Station neighborhood criteria for precipitation

Neighborhood level	Distance
I	< 3.0 km
II	< 5.0 km

QC-layer 7: External reference check In layer 7 relative humidity and air pressure data are compared to external data measured by the ZAMG stations Bad Gleichenberg and Feldbach. To be comparable, the air pressure data are reduced to a reference altitude of 300 m using the barometric formula (Equation 2.1) with H being the scale height, p_r and p being the reference value and the measured value, respectively, and h_r and h being the reference altitude (300 m) and the altitude of the candidate station, respectively. The scale height H is specified as 8 km.

$$p_r = p \cdot e^{-\frac{(h_r - h)}{H}} \tag{2.1}$$

3 Evaluation of the Quality Control System

In this chapter the results of an evaluation of the Quality Control System (QCS) are presented. First a statistical analysis of the Quality Flags (QFs) that had been given so far was done. Then the validity of several bounds and check parameters was tested and finally the performance of the QCS when confronted with typical rain gauge malfunctions and snowfall events was assessed. All this evaluation was done for the existing Quality Control System, Version 2 (QCSv2).

3.1 Statistical Analysis of Quality Flags

For a first evaluation of the QCS, a statistical analysis of the QFs was done. The aim of this analysis was to assess the data quality and to find possible starting points for improvement. The fraction of flagged data, the fraction of flagged data per QC-layer and the seasonal distribution of QFs were computed for each measured parameter. Included were all database entries that had been measured before August 2012. The output was searched for any unexpected or unreasonable values that might indicate an error or point out possible improvements. Since the numbers for precipitation are biased by the times when there is no precipitation at all, the analysis of flagged data was also done for *precipitation times* only. Precipitation times were defined as all measurement times with precipitation greater than 0.2 mm/5 min at at least one station of the WegenerNet.

3.1.1 Fraction of quality flagged data

As shown in the next few subsections, the QCS sometimes mistakes correct data for defective data and vice versa, but nevertheless the fraction of quality flagged data is a good first indicator of data quality.

The fraction of flagged data for each parameter is shown in Table 3.1. A fraction of about 6.7 % of all data is flagged. However, this is due to the high fraction of flagged relative humidity data (21.5 %), because of special contamination problems with humidity sensors (Kabas 2012; Kirchengast et al. 2014). When excluding relative humidity data, only 1.4 % of the data are flagged. The best quality is achieved for air temperature data with only 0.5 % of the data flagged. Four to five percent of the wind parameter data are flagged. An exception is the peak gust direction data with about 2.5 % of the data flagged.

Table 3.1: Fraction of quality flagged data (QCSv2).

Parameter	**Fraction of flagged data**
All Data	6.72 %
Air Temperature	0.54 %
Relative Humidity	21.48 %
Precipitation	1.17 %
Precipitation (Prec. Times)	4.99 %
Wind Direction	4.71 %
Wind Speed	4.71 %
Peak Gust	4.17 %
Peak Gust Direction	2.57 %
Soil Temperature	12.06 %
pF-Value	11.73 %
Air Pressure	5.70 %
Net Radiation	5.81 %

The fraction of flagged data seems quite high for the soil parameters. About 12 % of both soil temperature and pF-value data are flagged. However, this is due to a known transmission problem. Soil parameter data are sometimes sent twice by the logger. Additionally to the correct values, the same values are sent again with slightly different measurement times. Since these wrong times are flagged by the QCS, the fraction of flagged data is artificially high, while there are indeed correct measurements for most measurement times. Taking this into account, the quality of soil parameter data is quite good. The situation for air pressure and net radiation is similar. For both parameters about 6 % of the data are flagged. This fraction is, however, biased by a period of logger malfunction in spring 2011. The fraction of flagged precipitation data is relatively low with about 1.2 %. When looking at times of precipitation events only, the fraction is higher with about 5 % of the precipitation data flagged.

3.1.2 Quality Control Layer distribution of quality flags

While flags given in the QC-layers 1 and 2 correspond to missing or obviously wrong values, flags given in higher layers might be false alarms. Therefore a relatively high fraction of data flagged in a layer higher than 2 might be an indicator of too strict algorithms or boundary values. All parameters with fractions larger than 0.1 % in one of those layers are discussed below. The fraction of quality flags given by each layer is shown in Table 3.2.

About 0.24 %, 2.11 % and 17.3 % of the relative humidity data are flagged in layer 4, 6 and 7, respectively. While the latter fraction is remarkably large, the bad performance

Table 3.2: Fraction of quality flagged data per QC-layer (QCSv2).

QC-layer	**1**	**2**	**3**	**4**	**5**	**6**	**7**
All Data	0.68 %	1.17 %	0.01 %	0.07 %	0.12 %	0.66 %	4.58 %
Air Temperature	0.50 %	<0.01 %	<0.01 %	<0.01 %	-	0.04 %	-
Rel. Humidity	0.56 %	3.38 %	0.04 %	0.24 %	-	2.11 %	17.30 %
Precipitation	0.50 %	0.05 %	-	<0.01 %	0.36 %	0.27 %	-
Prec. (Prec. Times)	0.43 %	0.05 %	-	<0.01 %	2.16 %	2.46 %	-
Wind Dir.	2.09 %	2.49 %	-	0.03 %	0.12 %	-	-
Wind Speed	2.09 %	2.54 %	<0.01 %	<0.01 %	0.07 %	-	-
Peak Gust	1.81 %	2.35 %	<0.01 %	0.00 %	0.04 %	-	-
Peak Gust Dir.	0.13 %	2.30 %	-	0.04 %	0.14 %	-	-
Soil Temperature	9.11 %	2.63 %	0.01 %	0.32 %	-	-	-
pF-Value	9.10 %	2.62 %	0.00 %	<0.01 %	-	-	-
Air Pressure	0.40 %	5.27 %	0.00 %	0.01 %	-	-	0.02 %
Net Radiation	0.40 %	5.27 %	0.01 %	0.12 %	-	-	-

of the humidity sensors is known and these values could likely be justified.

Regarding precipitation data, the layers 5 and 6 play an important role. The relatively large contribution of layer 5 (0.36 % for all times, 2.16 % for precipitation times) can be explained by the flagging of precipitation measured while the temperature is below 2 °C, whereas the high fraction of data flagged in layer 6 (0.27 % for all times, 2.46 % for precipitation times) might indicate a relatively high fraction of false alarms.

The fraction of the wind direction and peak gust direction data flagged in layer 5 is 0.12 % and 0.14 %, respectively. These high values could be due to the close links between all four wind parameters within several layer 5 checks.

About 0.32 % of the soil temperature data and about 0.12 % of the net radiation data are flagged in layer 4. These values might possibly indicate too strict boundary values. However, since there are comparatively few measurements of both parameters, the fractions might as well be biased by distinct events of malfunction.

The remarkably large fractions of soil parameter data flagged in layer 1 and air pressure and net radiation data flagged in layer 2 can be attributed to the transmission problem and the period of logger malfunction mentioned above.

3.1.3 Seasonal distribution of Quality Flags

A large fraction of air temperature flags are set in winter. This could indicate an increased probability of sensor malfunction, logger malfunction or transmission problems due to low temperatures. The large fraction of precipitation data flagged in winter is largely due to the flagging of precipitation measured while the temperature is below 2 °C in QC-layer 5. The data quality of relative humidity is bad throughout the year. For all other parameters conclusions can not be drawn, because, due to the relatively

Table 3.3: Seasonal distribution of quality flagged data (QCSv2).

Season	**MAM**	**JJA**	**SON**	**DJF**
All Data	23 %	22 %	27 %	27 %
Air Temperature	26 %	8 %	16 %	50 %
Rel. Humidity	22 %	23 %	30 %	25 %
Precipitation	24 %	15 %	16 %	46 %
Wind Direction	42 %	14 %	10 %	35 %
Wind Speed	42 %	14 %	10 %	35 %
Peak Gust	26 %	28 %	22 %	22 %
Peak Gust Direction	29 %	29 %	19 %	23 %
Soil Temperature	23 %	26 %	23 %	29 %
pF-Value	22 %	25 %	23 %	30 %
Air Pressure	57 %	35 %	8 %	1 %
Net Radiation	56 %	35 %	7 %	1 %

small number of sensors, the distribution is probably biased by distinct time periods of malfunction. This can be seen most exemplary for the parameters air pressure and net radiation. Due to the malfunction of the logger in spring 2011, more than 50 % of their flags originate in spring. The seasonal distribution of quality flagged data is shown in Table 3.3, in units percent of all flagged data of a parameter.

3.2 Validity of Boundaries and Check Parameters

In a next step to assess the QCS, the validity of several boundaries and check parameters was tested. Case studies revealed that the climatological boundaries for relative humidity (checked in QC-layer 3) and precipitation (checked in QC-layer 4) are too strict. Also the tendency of the QC-layer 6 check to be too strict is discussed in this section.

3.2.1 Validity of Relative Humidity Climatological Boundaries

Relative humidity data are checked against climatological boundaries in QC-layer 3, with the lower climatological boundary value being 20 % for all months. Since the start of the WegenerNet in 2007, there were three days when this boundary value was exceeded at several stations and for several hours. The percentage of relative humidity measurements exceeding the boundary value at each of these three days is shown in Table 3.4. On two of these days, April 09, 2011 and February 18, 2008, the low humidity can be attributed to distinctive north foehn events.

A detailed case study was done for April 9, 2011. The relative humidity measured at each station at 13:10 UTC is shown in Figure 3.1. The time series of air temperature, relative humidity, wind speed and wind direction at several stations are shown in Fig-

Table 3.4: Fraction (percentage) of measurements with a relative humidity below 20 % (QCSv2).

Date	Measurements
Jan. 27, 2008	5.8%
Feb. 18, 2008	11.7%
Apr. 09, 2011	11.5%

ure 3.2. Both temporal and spatial behavior show no sign of malfunction and indicate that a relative humidity of down to 13 % is indeed possible.

3.2.2 Validity of Precipitation Climatological Boundaries

For precipitation data, the check against climatological boundaries is not done in QC-layer 3, but in QC-layer 4 for technical reasons. Four events were identified during which these boundaries were exceeded at several stations. All of them were convective rainfall events. For each event the date, the climatological boundary value of the respective month, the maximum rainfall intensity and the number of measurements exceeding the boundary value are given in Table 3.5.

Table 3.5: Date, climatological boundary value of the respective month, maximum rainfall intensity and number of measurements exceeding the climatological boundary value of four precipitation events during which the climatological boundaries were exceeded (QCSv2).

Date	Boundary	Max. Intensity	Measurements
Dec. 25, 2009	8.5 mm/5 min	8.8 mm/5 min	2
Aug. 19, 2011	12.5 mm/5 min	14.0 mm/5 min	5
Apr. 05, 2012	4.5 mm/5 min	6.8 mm/5 min	9
May 31, 2012	11.0 mm/5 min	11.8 mm/5 min	2
Apr. 22, 2013	4.5 mm/5 min	7.2 mm/5 min	23

In order to analyze the spatial and temporal behavior of precipitation patterns and to identify deficient measurements, series of plots were made for each of these precipitation events. For each five minute interval the Level 1 five minute precipitation sum of each station is plotted at the coordinates of the respective station, with the color of the marker indicating the QFs given by the QCS. Additionally the corresponding Level 2 grid data were plotted in order to better visualize the spatial pattern of the precipitation. In Figure 3.3 such plots for April 22, 2013 at 16:55 UTC and 17:00 UTC are shown. This type of plots was used for several applications and will hereafter be referred to as

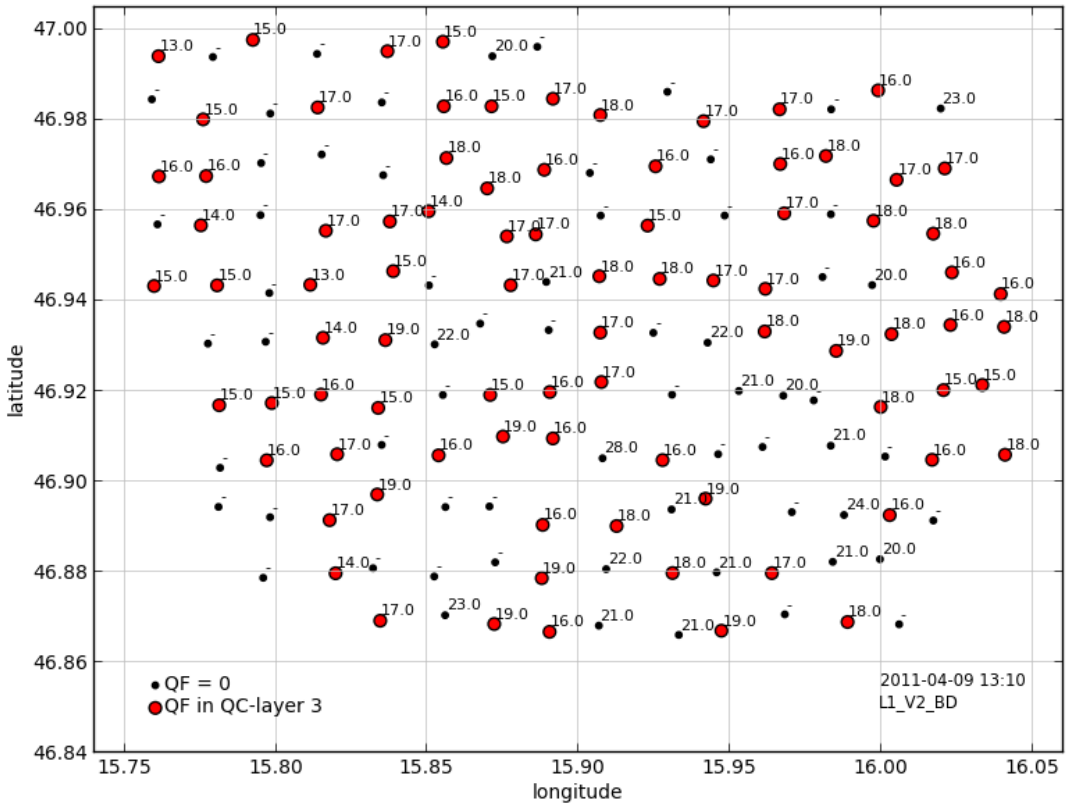

Figure 3.1: Relative humidity Level 1 data in % on April 9th, 2011 at 13:10 UTC. Red markers indicate data values flagged in QC-layer 3.

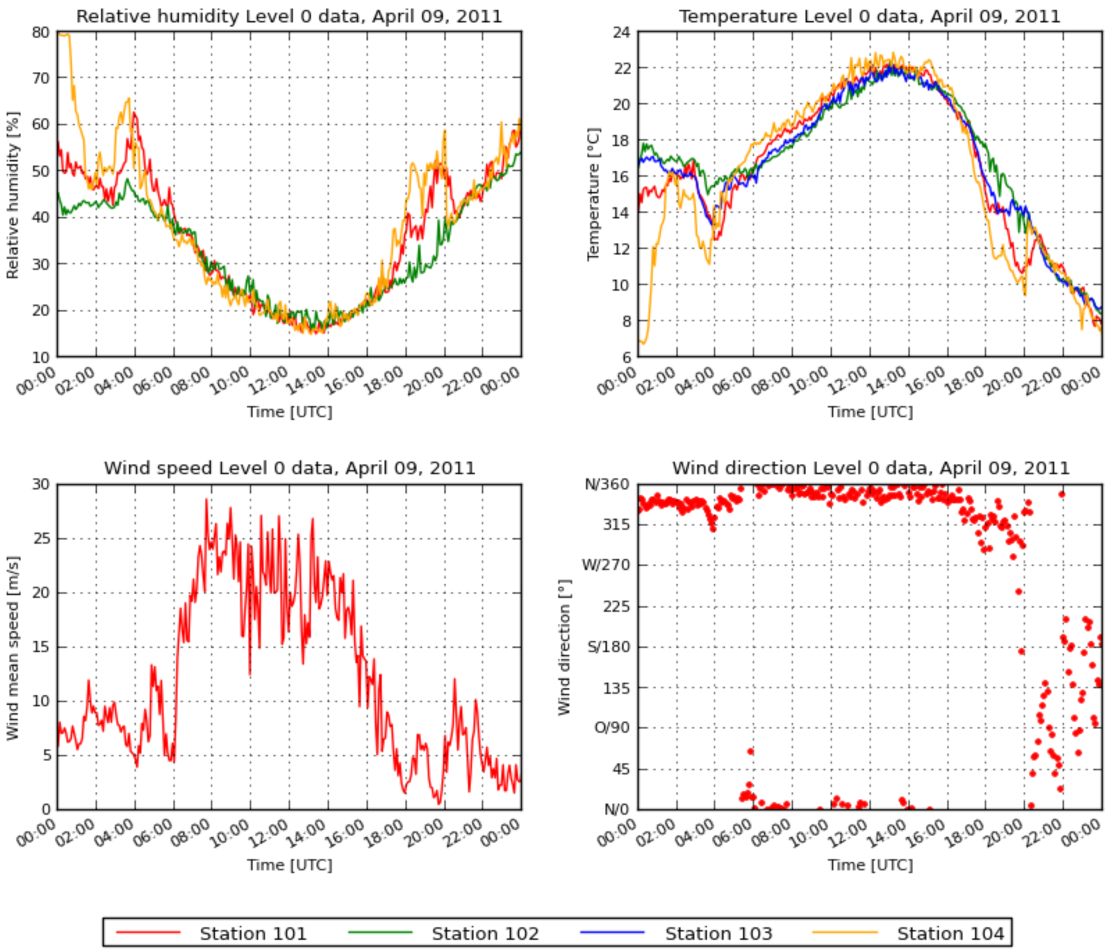

Figure 3.2: Relative humidity, air temperature, wind speed and wind direction Level 0 data on April 9th, 2011 at several stations adjacent to each other.

precipitation plots.

Visual reviews of these plots and time series of individual stations revealed no sign of rain gauge malfunction and indicated that the climatological boundaries for precipitation are, at least for the months April, May and August, indeed too strict.

3.2.3 Validity of Quality Control Layer 6 Check Parameters for Precipitation

Since the statistical analysis of quality flags suggested that there might be a high number of false alarms in QC-layer 6 for precipitation data (see Subsection 3.1.2), flags given by this layer were analyzed as well. Using the same kind of plots as in Subsection 3.2.2 and the time series of individual stations, the precipitation patterns of several case studies were searched for obviously defective data (e. g. from blocked rain gauges). The results were compared to the respective set of data values flagged in QC-layer 6.

This comparison revealed that QC-layer 6 tends to be too strict when confronted with extreme spatial gradients in precipitation patterns, which occur frequently during convective precipitation events. As illustrated in Figure 3.4, the five minute precipitation sums can vary by more than 7 mm within 3 km. Regarding the hourly precipitation sums, differences larger than 12 mm within 5 km are possible.

Also measurements at stations near the edges of the WegenerNet are more likely to be flagged due to the lower number of neighbors.

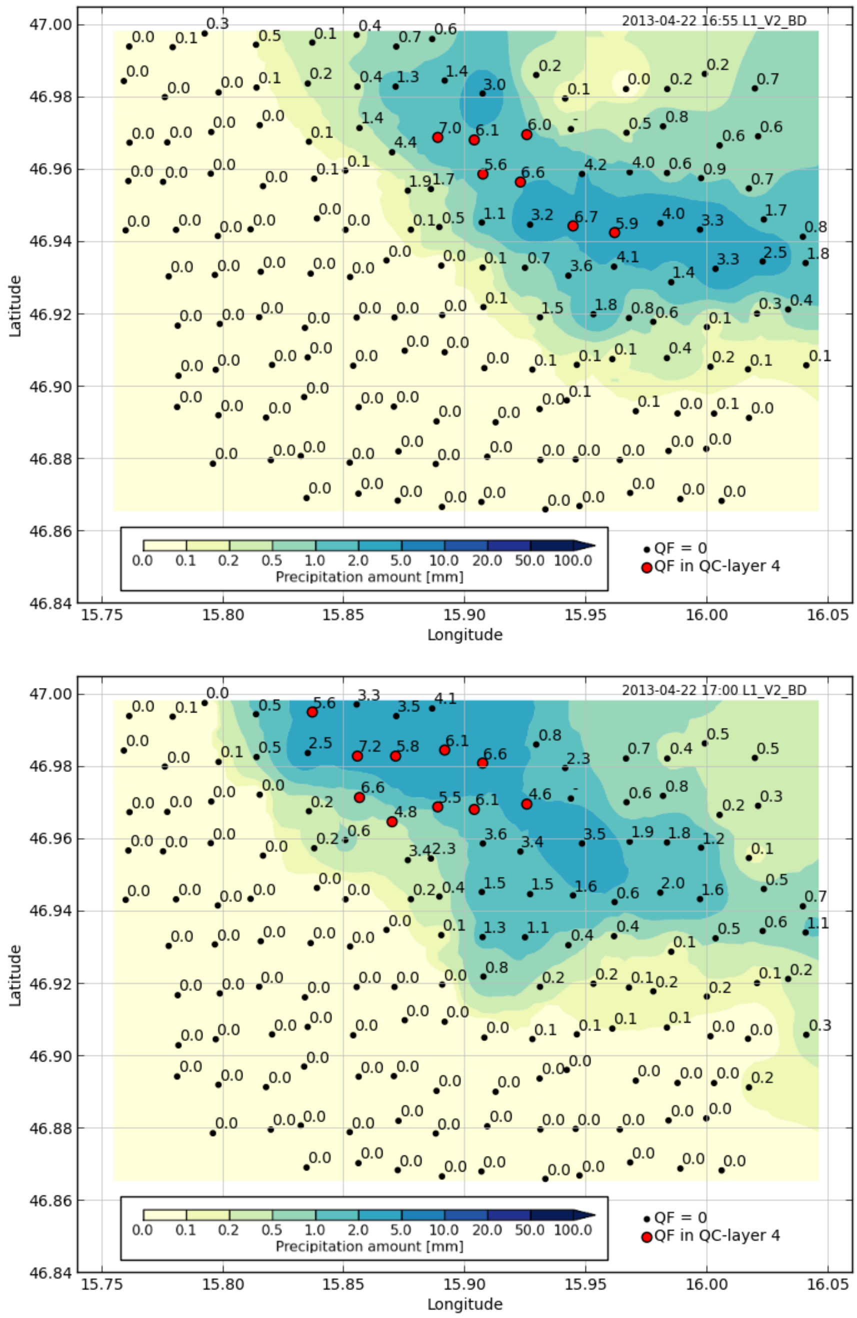

Figure 3.3: Five minute precipitation sums in mm (Level 0 data, numbered dots) and grid data (Level 2 data, colored contours) on April 22, 2013 at 16:55 UTC (upper) and 17:00 UTC (lower). Red markers indicate data values flagged in QC-layer 4.

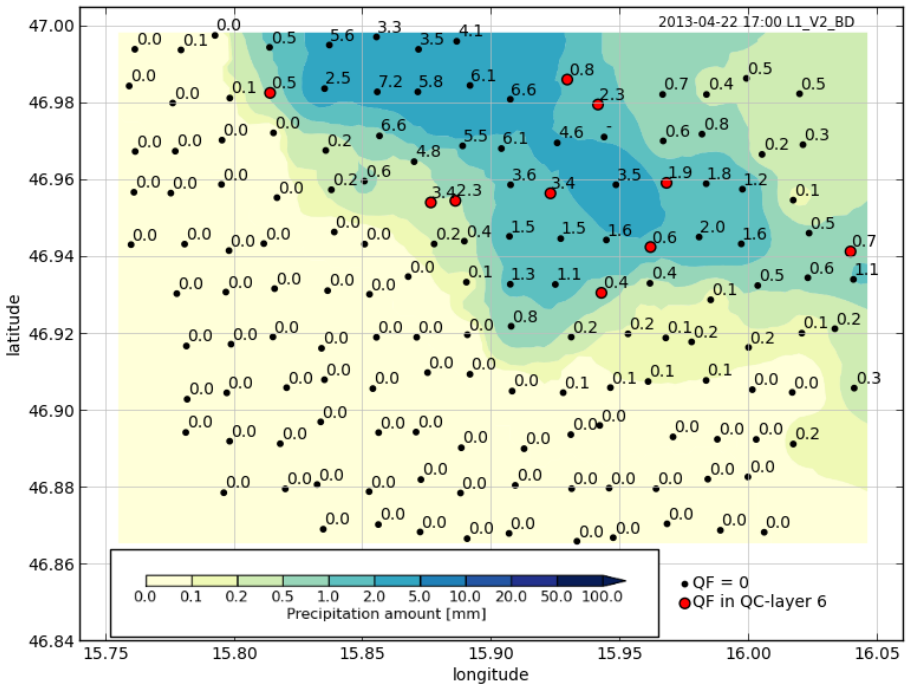

Figure 3.4: Five minute precipitation sums in mm (Level 0 data, numbered dots) and grid data (Level 2 data, colored contours) on April 22, 2013 at 17:00. Red markers indicate data values flagged in QC-layer 6.

3.3 Test of Algorithms

The performance of the QCS algorithms when confronted with three typical rain gauge malfunctions was assessed by analyzing ten malfunction events each. Furthermore case studies revealed two weaknesses of the QCS algorithms related to snowfall events.

3.3.1 Rain Gauge Malfunction Scenarios

Besides electronic malfunctions, which usually produce fail values or obviously wrong values and therefore can easily be detected, blockages (e. g. due to leaves, seeds, pollen) are the most common malfunction of a rain gauge. Two typical forms of blockages, depending on the progress of the blockage, can be distinguished:

Total blockages occur if a rain gauge is entirely or nearly entirely blocked, so that the measured precipitation sums do not exceed 0.1 mm/5 min.

Partial blockages occur if the opening of the rain gauge is not yet blocked entirely, but enough to limit the amount of water that can pass the blockage. Given large enough precipitation intensities, water accumulates in the gauge. As a result precipitation peaks are underestimated, while lower intensities shortly after a peak are overestimated and there is precipitation measured even after the actual precipitation event is over (up to several hours).

While a strict dividing line can not be drawn, each form shows a more or less characteristic behavior in the time series of precipitation sums.

Another possible source of defective data from rain gauges are **flushes**. Natural flushes can happen if a total blockage is cleared for some reason and water that had been accumulated some time ago is suddenly measured then. However, these events are rare. More important are artificial flushes, although they are not malfunctions of the rain gauges in the strict sense. They are carried out by the maintenance staff of the WegenerNet in order to clear blockages of the precipitation gauges by pouring about 0.5 l of water into the gauge. Usually the date, but not the exact time of an artificial flush is documented and therefore it is a task of the QCS to detect the measurements falsified by these flushes. Examples of flushes, total and partial blockages are shown in Figure 3.5.

The ability of the QCS to detect flushes and both kinds of blockages was assessed by comparing Level 0 data and Level 2 data time series and classifying the performance of the QCS into:

1. detected: all measurements were flagged correctly
2. partly detected: a large part of the measurements was flagged correctly

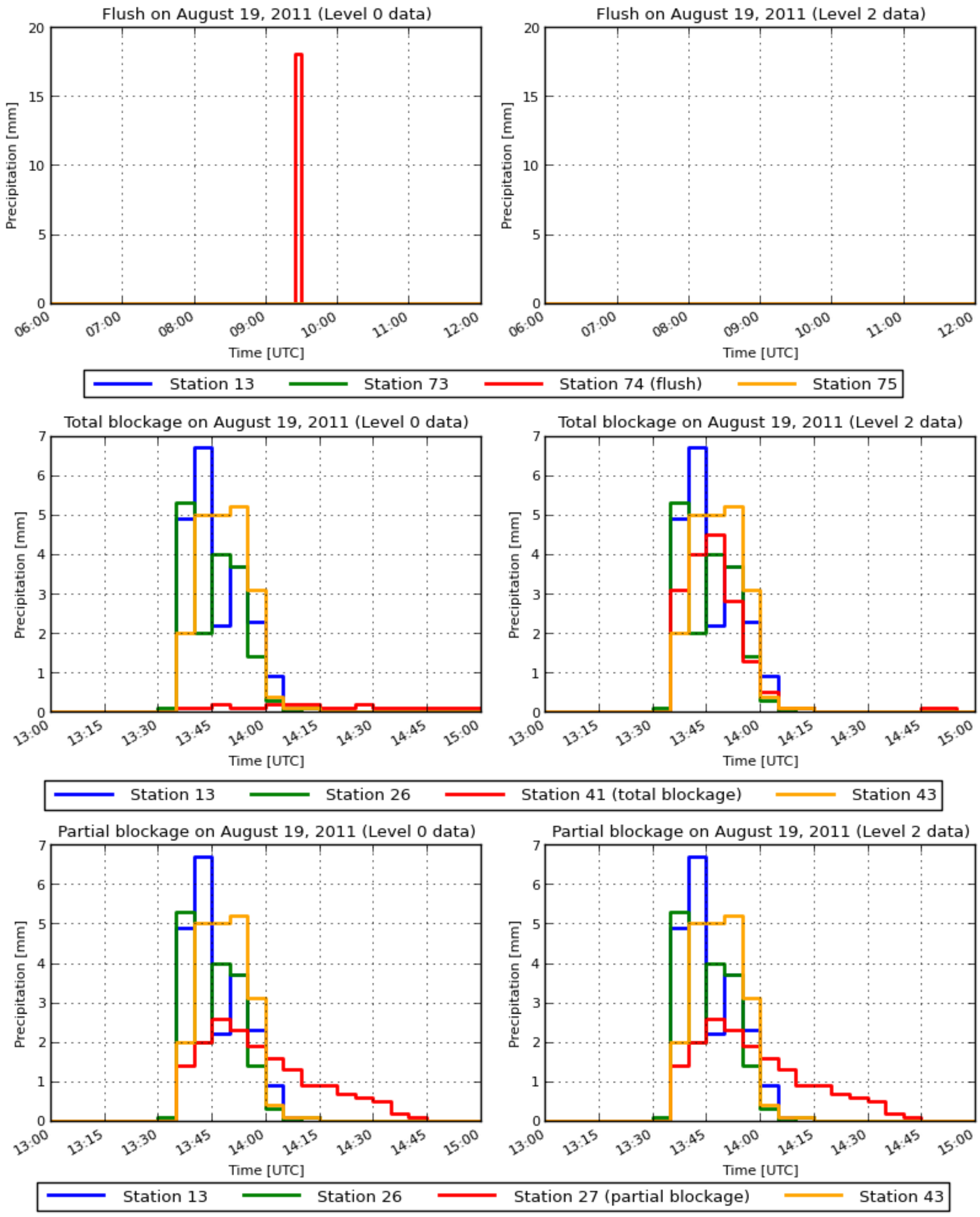

Figure 3.5: Examples of typical rain gauge malfunctions. Five minute precipitation sums of an artificially flushed (nr. 74), a totally blocked (nr. 41) and a partially blocked station (nr. 27) plus several neighboring stations in level 0 data (left) and level 2 data (right), during a precipitation event on August 19, 2011. While the flush and the total blockage are detected and corrected, the QCS algorithms fail to detect the partial blockage.

Table 3.6: Number of detected, partly detected and not detected malfunction events (QCSv2).

Type	**Detected**	**Partly detected**	**Not detected**
Flushes	9	1	0
Total blockages	5	4	1
Partial blockages	3	4	3

3. not detected: all measurements were flagged incorrectly

Ten malfunction events of each malfunction type were analyzed. The results are given in Table 3.6, a list of the events is given in Table 3.7.

Nine out of ten flushes were identified and flagged correctly by the QCS. However, the first or last measurement of a flush event can slip through the QCS, if only a very small part of the respective measurement period is affected by the flush event and therefore the precipitation sum measured within this period is very small.

While total blockages happen quite frequently, they are usually detected quite well by QC-layer 6. Five out of ten events were flagged correctly throughout the whole precipitation event. However, when confronted with extreme spatial gradients (see also Subsection 3.2.3), QC-layer 6 sometimes fails to detect total blockages during large parts of a precipitation event (four events). Only one total blockage was not detected at all.

Partial blockages are easy to detect visually, but were often not detected (three events) or only partly detected (four events) by the QCS. Only three out of ten partial blockages were treated correctly throughout the precipitation event.

3.3.2 Snowfall events

Case studies of snowfall events revealed two more weaknesses of the QCS:

1. measurements from unheated precipitation gauges are not flagged during snowfall events,
2. melting snow is interpreted as a precipitation event.

During snowfall events: As expected, heated gauges measure precipitation during snowfall events, while unheated gauges measure no precipitation. However, there was a major weakness in the QC-layer 5, rule 2 algorithm: measurements from unheated gauges are only flagged if the air temperature is below 3 °C and a precipitation sum of at least 0.1 mm/5 min is measured. Due to this implementation, precipitation sums of 0 mm at unheated gauges are treated as being correct, even if there indeed is a snowfall event. Moreover correct measurements at heated gauges are sometimes overruled by unheated neighbors and thus flagged in QC-layer 6. This results in obviously wrong Level

Table 3.7: List of analyzed malfunction events (QCSv2).

Type	**Date**	**Time**	**Station**	**Detected**
Flush	Jun. 11, 2012	13:55	3	yes
	Jun. 11, 2012	14:10	25	yes
	Jun. 11, 2012	14:25	27	yes
	Jun. 11, 2012	15:40	150	yes
	Jun. 30, 2012	09:05	37	yes
	Jun. 30, 2012	09:30	74	yes
	Jul. 19, 2012	13:35	74	yes
	Jan. 16, 2013	10:05-10:10	82	partly
	Jan. 16, 2013	10:35-10:40	135	yes
	Jan. 16, 2013	11:00-11:05	132	yes
Total blockage	Aug. 3, 2011		11	yes
	Aug. 3, 2011		32	yes
	Aug. 3, 2011		46	partly
	Aug. 3, 2011		58	yes
	Aug. 3, 2011		66	partly
	Aug. 3, 2011		82	partly
	Aug. 19, 2011		41	yes
	Jun. 11, 2012		40	yes
	Jun. 11, 2012		74	no
	Jun. 11, 2012		135	partly
Partial blockage	Aug. 3, 2011		27	partly
	Aug. 3, 2011		41	yes
	Aug. 3, 2011		43	no
	Aug. 3, 2011		44	yes
	Aug. 3, 2011		94	partly
	Aug. 19, 2011		27	no
	Oct. 7, 2011		35	yes
	Apr. 5, 2012		41	partly
	Jul. 15, 2012		55	partly
	Sep. 1, 2012		1	no

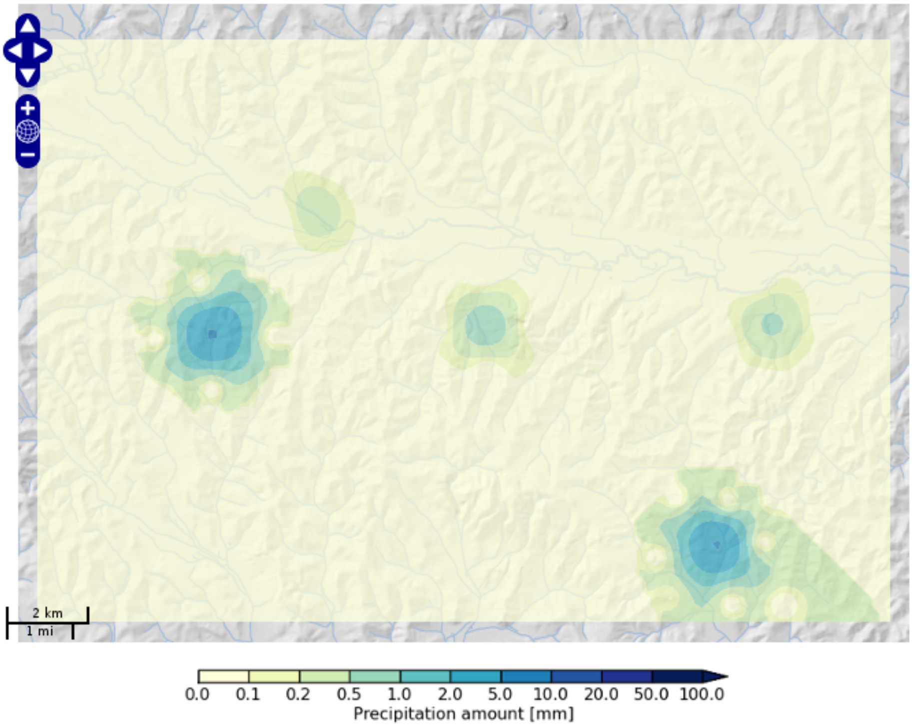

Figure 3.6: Daily precipitation sums (Level 2 grid data) of a snowfall event on January 16, 2013.

2 data products, most clearly to be seen in grid data products. Even intense grid-wide snowfall events are interpreted as light snowfall in an area of some kilometers around stations with heated gauges and no snowfall in the rest of the area. An example from January 2013 is shown in Figure 3.6.

Melting snow: On unheated gauges snow is accumulating during snowfall events. When temperature rises the snow melts and is interpreted as rainfall. By contrast, heated gauges melt and measure the snow during the snowfall event. There is no accumulation of snow and therefore no precipitation is measured when temperature rises. Again these correct measurements are often overruled by the larger number of incorrect measurements in QC-layer 6. As a consequence the Level 2 data products show precipitation in grid data and even in station data of the heated stations during such melting events. An example is shown in Figure 3.7. On March 18, 2013 there was mixed rain and snow precipitation. With rising temperatures on March 19, 2013, all unheated gauges measured precipitation, while the heated gauges did not measure precipitation. The melting yields precipitation sums up to 2.5 $\mathrm{mm\,h^{-1}}$ (artificially in terms of their time of occurrence) .

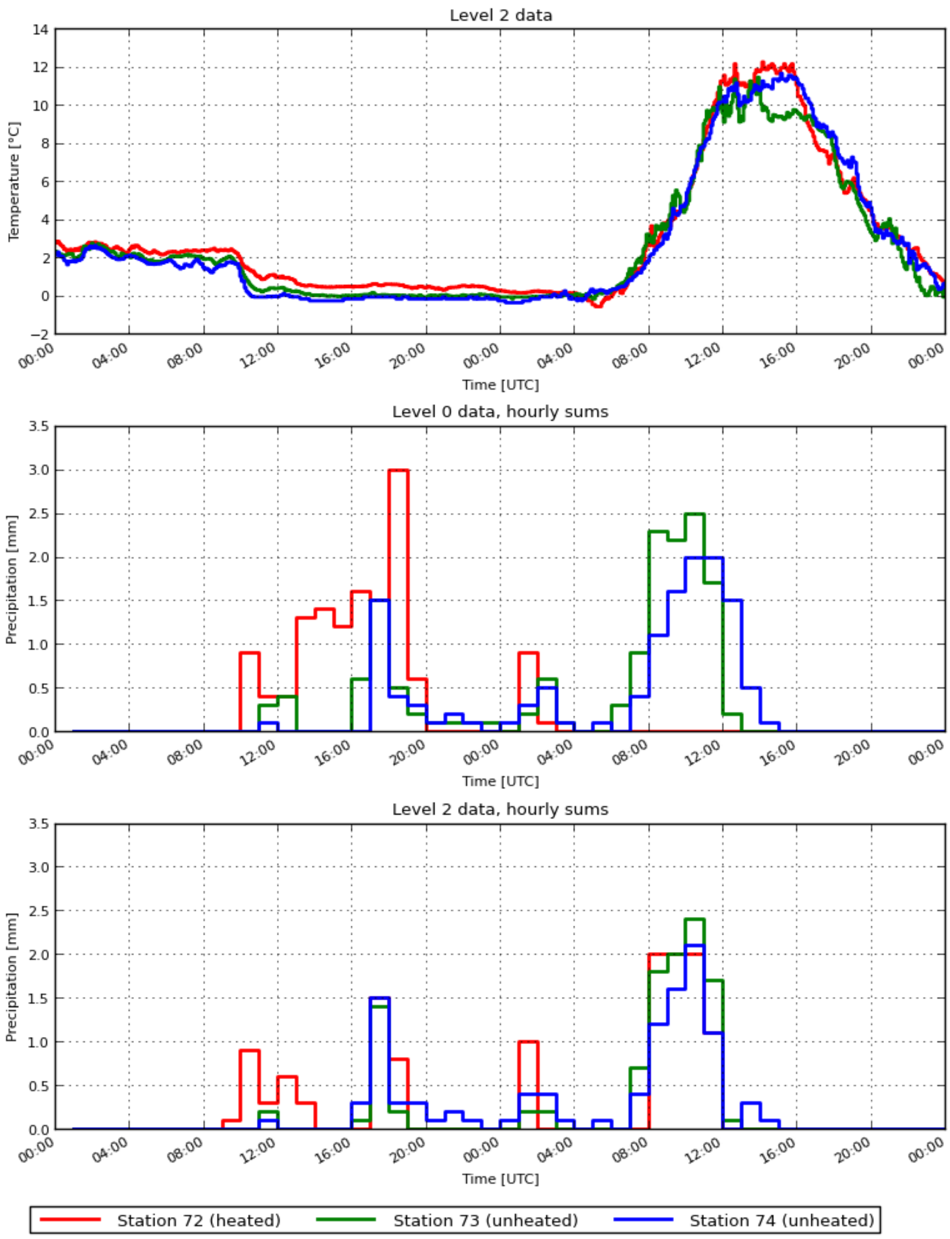

Figure 3.7: Temperature (Level 2 data) and hourly precipitation sums (Level 0 and Level 2 data) from March 18, 2013 00:00 UTC to March 20, 2013 00:00 UTC, for heated and unheated rain gauges.
March 18: mixed rain and snow precipitation, March 19: with rising temperatures the snow that accumulated on unheated gauges melts.

4 Improvement of the Quality Control System

In this chapter the improvements done to the Quality Control System (QCS) are presented. They are mostly based on the findings of Chapter 3 and can be grouped into four topics:

1. the revision of some climatological boundary values,
2. an improved detection of rain gauge malfunctions and less false alarms in the interstational check,
3. modifications of the QCS related to the problems with snowfall events, and
4. an improved processing speed.

Some other modifications to the code are summarized in the final section of the chapter. Hereafter the current (“old”) version of the QCS will be referred to as Quality Control System, Version 2 (QCSv2), as was done in Chapter 3, whereas the improved version is referred to as Quality Control System, Version 3 (QCSv3).

4.1 Modifications of Climatological Boundary Values

As shown in Section 3.2, several climatological boundaries of QCSv2 are too strict and were revised for Quality Control System, Version 3 (QCSv3).

Relative Humidity: Case studies revealed that a relative humidity down to 13 % is possible (see Subsection 3.2.1). Therefore the lower climatological boundary value was changed from 20 % to 10 %.

Precipitation: Case studies revealed that the upper climatological boundary values of precipitation for the months April, May, August and December were too strict (see Subsection 3.2.2). After consultation with the WegenerNet team, new monthly boundary values were defined. Figure 4.1 shows the old and new boundary values as well as the maximum measured values of both ZAMG and WegenerNet stations.

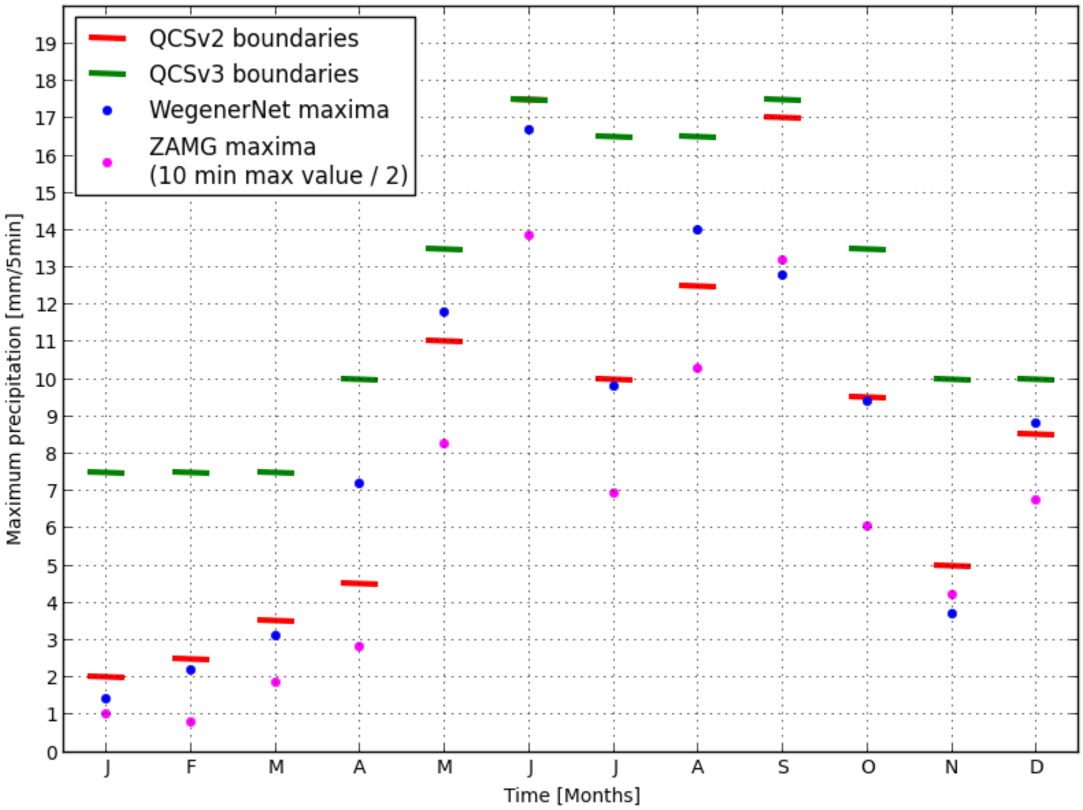

Figure 4.1: Monthly QCSv2 and QCSv3 precipitation boundary values in QC-layer 4, precipitation maxima measured in the WegenerNet and precipitation maxima measured at the ZAMG stations. ZAMG data include measurements at the ZAMG stations Bad Gleichenberg and Feldbach since August 16, 1999 and April 08, 2003, respectively. The plotted ZAMG maxima are the 10 minute maxima divided by two.

4.2 Modification of the Interstational Checks

The main targets of the modifications done to QC-layer 6 were to improve the detection of blockages (see Section 3.3) and to reduce the number of false alarms, especially when dealing with extreme spatial gradients (see Subsection 3.2.3). The QC-layer 6 checks of temperature and relative humidity were not changed.

In QCSv2 there was only one interstational check for precipitation data in QC-layer 6, which basically flagged measurements that were too different from measurements at neighboring stations (see Section 2.2). The concept for QCSv3 was to implement several more simple, but also more specialized checks, each searching for a specific typical malfunction. These specialized checks have two advantages:

1. the check parameters can be tuned to specific malfunctions, allowing a better overall performance and

2. the different malfunctions are distinctly marked, providing more information for the WegenerNet maintenance team.

A total of four new checks was developed and implemented. Also a part of the old algorithm was basically retained with revised check parameters as maxdiff check. For each check appropriate data from at least five neighbors are needed, otherwise a no_ref flag is applied.

4.2.1 Maxdiff Check (rule 0)

The maxdiff check corresponds to the part of the QCSv2 interstational check, that checked the 60 minute precipitation sums against the respective sums of neighboring stations. In QCSv3, a candidate value is flagged by the maxdiff check if

$$|C - \text{median}(N)| > d$$

where C denotes the 60 minute precipitation sum of the candidate, N denotes the 60 minute precipitation sums of the neighbors and

$$d = \max \begin{pmatrix} d_1 * \min((\max(N) - \text{median}(N)), (\text{median}(N) - \min(N)) \\ d_2 * \text{median}(N) \\ 1.0 \end{pmatrix}$$

where $d_1 = 2.0$ and $d_2 = 0.25$. While the basic algorithm is the same as in QCSv2, the factors d_1 and d_2 were changed from 1.2 and 0.2 to 2.0 and 0.25, respectively, in order to allow more extreme spatial gradients. The new factors were derived as follows:

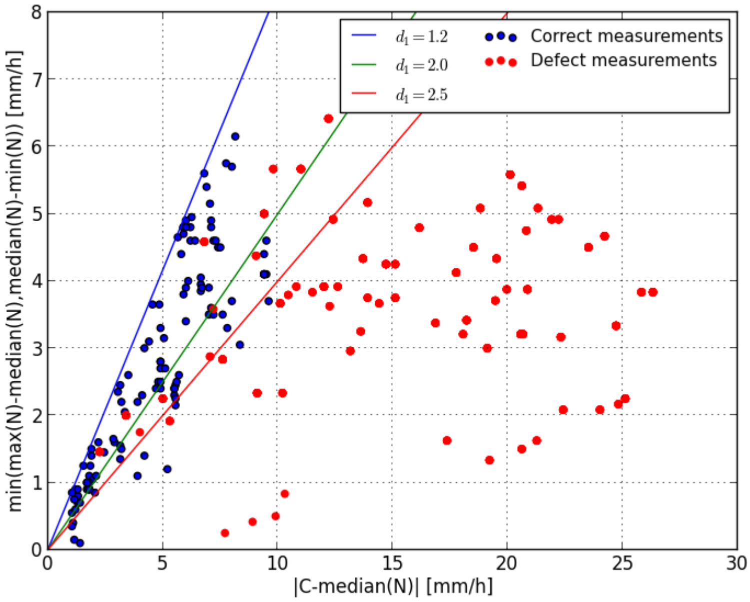

Figure 4.2: Maxdiff check terms of several measurements flagged in QCSv2.

Factor d_1: All measurements of two case studies on April 22, 2013 and August 19, 2011, that had been flagged in QCSv2, were analyzed using precipitation plots. They were classified into correct and defect measurements (unclear cases were excluded). Also data from stations at the edge of the WegenerNet were excluded to avoid possible effects due to the lower number of neighbors. For each of these measurements the terms

$$|C - \text{median}(N)|$$

and

$$\min((\max(N) - \text{median}(N)), (\text{median}(N) - \min(N))$$

were plotted against each other in a scatterplot, which is given in Figure 4.2. A line with the slope d_1 divides the measurements that pass the check due to the term

$$d_1 * \min((\max(N) - \text{median}(N)), (\text{median}(N) - \min(N))$$

from the measurements that do not. Flagged measurements are on the downright side of the line, unflagged measurements are on the top left side. On the basis of this plot, the new factor $d_1 = 2.0$ was chosen.

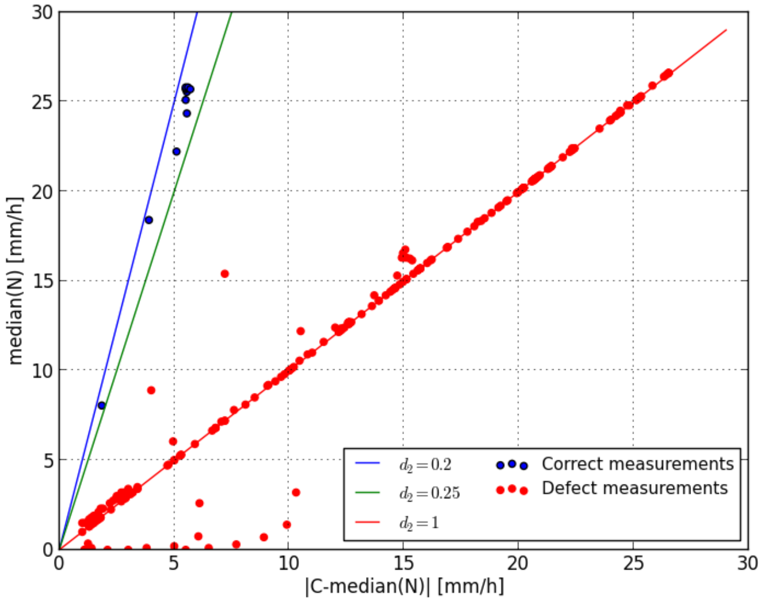

Figure 4.3: Maxdiff check terms of several measurements flagged in QCSv2.

Factor d_2: Out of the correct measurements used above, those were identified for which d is defined by the term $d_2 * \text{median}(N)$. For each of these measurements and the defect measurements already used above, the terms

$$|C - \text{median}(N)|$$

and

$$\text{median}(N)$$

were plotted against each other in a scatterplot, which is given in Figure 4.3. A line with the slope d_2 divides the measurements that pass the check due to the term

$$d_2 * \text{median}(N)$$

from the measurements that do not.

The points exactly on the line with slope $d_2 = 1$ are measurements from totally blocked rain gauges, the points close to the x-axis are measurements from partially blocked stations after the actual precipitation event is over. On the basis of this plot, the new factor $d_2 = 0.25$ was chosen.

4.2.2 Flush Check (rule 1)

Even though the detection of flushes was already good in QCSv2, a new further improved flush check was implemented in QCSv3. A candidate value is flagged if the 10 minute precipitation sum C is > 0.49 mm AND the maximum of the 15 minute precipitation sums of the neighbors N is < 0.11 mm. This flush check is basically equivalent to the first part the of old interstational check, but has two advantages:

- Since the 10/15 minute precipitation sums are checked instead of the 60 minute sums, interference with rainfall shortly before or shortly after the flush is diminished.
- The flush events are now distinctly marked, improving the documentation of artificial flushes.

4.2.3 Total Blockage Check (rule 2)

The total blockage check consists of two parts. The first part is a straightforward check for very little to no precipitation, while there is more precipitation at the neighbors. A candidate value is flagged if the 5 minute precipitation sum C is < 0.11 mm AND the minimum of the 5 minute precipitation sums of the neighbors N is > 0.49 mm.

The second part ensures that once a rain gauge is detected to be totally blocked, all following measurements from this gauge are flagged until the blockage is cleared (i.e. precipitation is measured again). A candidate value is flagged, if the value five minutes before was flagged in the total blockage check AND the 5 minute precipitation sum C is < 0.11 mm. The total blockage check provides four advantages over the old interstational check:

- Total blockages are distinctly marked.
- The new check is more reliable: Gauges that are once identified as totally blocked are treated as such until they measure precipitation again.
- The new check is more robust in regard to extreme spatial gradients.
- The old algorithm had a tendency to detect blockages only with a delay of one or two measurements. This is improved with the new check.

4.2.4 Partial Blockage Check (rule 3)

The partial blockage check takes advantage of the characteristic temporal behavior of partially blocked rain gauges in order to identify them. As described in Subsection 3.3.1, partially blocked gauges underestimate precipitation peaks and overestimate low intensities shortly after a peak, thus having a lower temporal variability than neighboring gauges.

As a measure of variability the summed up absolute differences of the precipitation sums of the last 20 minutes normalized by the total precipitation sum within this period is used. The detailed calculation rules of the variability at the candidate station τ_C and the mean variability of the neighbors τ_N are

$$\tau_C = \frac{\sum_{i=0}^{3} |C_i - C_{i+1}|}{\sum_{i=0}^{4} C_i}$$

$$\tau_N = \sum_j \left(\frac{\sum_{i=0}^{3} |N_{i,j} - N_{i+1,j}|}{\sum_{i=0}^{4} N_{i,j}} \right)$$

with C_i being the 5 minute precipitation sum at the candidate gauge at time step i. Time step 0 is the measurement time of the candidate value, time step 1 is the measurement time 5 minutes before, time step 2 is the measurement time 10 minutes before and so on. $N_{i,j}$ is the corresponding precipitation sum at neighbor j. A candidate value is flagged if

$$\frac{\tau_N}{\tau_C} > 2.5$$

which was found empirically to be an adequate threshold setting.

4.2.5 Fade Away Check (rule 4)

20 minutes after the actual precipitation event is over, the partial blockage check can no longer be applied because the precipitation sums at the neighboring stations are zero. In order to detect the tails of partial blockages nonetheless, the fade away check was implemented.

The check is applied if any value within the last 15 minutes at the candidate gauge was flagged in the partial blockage check or the fade away check. (A period of 15 minutes was chosen over a 20 minute period to reduce the number of false alarms.) A candidate value is then flagged if the 15 minute precipitation sum C is > 0.19 mm AND the maximum of the 5 minute precipitation sums of the neighbors N is < 0.01 mm.

4.3 Improved Treatment of Snowfall Events

In order to avoid the incorrect handling of unheated gauges during snowfall events (see Subsection 3.3.2), several modifications had to be done to different parts of the QCS.

The most obvious change is that data from unheated gauges are now flagged in QC-layer 5, rule 2 whenever the mean air temperature of the last five hours is below 2 °C (hereafter called *cold times*). In contrast to QCSv2, this is done regardless of the measured precipitation sum. The check is skipped if the mean air temperature of the whole processed period is above 3 °C.

The problem of heated stations being overruled by unheated stations in QC-layer 6 was avoided by accepting only reference data that were not flagged in the preceding QC-layers. This modification, however, has a downside effect during cold times: There are too few appropriate neighbors available and thus data from heated gauges are given a no_ref flag. As a consequence little to no data meet the requirements to be processed by the DPG and thus no Level 2 data are produced. In order to solve this problem, another flag was introduced. During cold times an *ignore no_ref* flag is given to data from heated stations. Data wearing this flag are processed in the DPG regardless of the no_ref flag in QC-layer 6.

In QC-layer 5, rule 4, the overruling of heated stations was solved by applying the check only if unflagged data from all three gauge models are available.

In QCSv2 all gauges of the types Young and Kroneis/Meteoservis were regarded as heated. However, it is known that the heating device of these nominally heated gauges was often malfunctioning (Szeberenyi 2014). Sometimes only three heated gauges were operating properly. In QCSv3 the information whether a rain gauge is in fact heated is queried from a database holding the malfunction periods of the heating devices.

At a more technical level, the structure of the QC-layer 5 source code was reworked and made more transparent.

4.4 Improvement of Processing Speed

Due to some additional checks (see Section 4.2), some checks being run more often (see Section 4.3) and the de facto introduction of *maxchecklevels* (see Section 4.5), the runtime of the QCS increased considerably. Depending on temperature and precipitation conditions, the increase amounted to a factor between 2 and 6, potentially threatening the near-real time processing of data.

In order to identify the parts responsible for the slowdown and potential points for improvement, a runtime analysis of the QCS was done using the python module *cProfile*. *cProfile* provides information about how much time is spent in each subroutine of a program and how often it is called. This analysis revealed that the slowdown is mainly due to the increased need for data from neighboring stations and for precipitation sums. Two parts of the QCS were identified that are particularly inefficient:

1. Every time the data of neighbors are needed, the function *getNeighbors* provides the information which stations are neighbors of a certain station. If this function is called, the neighbors for the specific date are queried, which is rather time-consuming. This process was sped up by checking whether there is a change in the neighborhood relations within the whole processed time period when starting

Table 4.1: Runtimes for processing one hour of data in QCSv2 and QCSv3.

Date	**Time [UTC]**	**Runtime [s]**		**Note**
		QCSv2	QCSv3	
Jan. 27, 2008	17:00-18:00	158	83	
Feb. 19, 2008	17:00-18:00	148	81	
Sep. 12, 2012	17:00-18:00	136	81	Precipitation
Jan. 11, 2013	17:00-18:00	141	83	$T < 2\,°\mathrm{C}$
Dec. 02, 2012	10:00-11:00	146	83	$T < 2\,°\mathrm{C}$, Precipitation

the QCS. If this is not the case, a fixed list of neighbors is accessed directly in the cache.

2. Every time a precipitation sum is computed, the information on which sensors measure which parameters is queried from the database by the function *get_paramid_measid*. This is unnecessary since these links are fixed. Improvement: The links are queried one time after starting the QCS and stored in the cache.

After these two parts were improved, the processing speeds were compared again and it turned out that the final QCSv3 is faster than QCSv2 by about 40 %. Exemplary runtimes are shown in Table 4.1, confirming the significantly faster processing speed of QCSv3 despite the more elaborated checks from the QCS improvements.

4.5 Further Improvements

Due to various good reasons, several other small modifications were made:

- The function *getMeanTemp*, which provides the mean air temperature of a certain time period, used Level 1 data, which it queried from the database. Since such data are actually not yet available when data are processed for the first time (i.e. the real-time processing), no mean temperature could be calculated and, as a result, rule 2 in QC-layer 5 did not work properly. This was solved by using unflagged data from the cache.

- The parameters of the QC-layer 5 check comparing the precipitation measurements at the reference station were modified, such that slightly larger differences between the different rain gauge models are allowed (0.21 mm/5 min | 0.31 mm/5 min | 30 % between gauges instead of 0.13 mm/5 min | 0.23 mm/5 min | 25 %, for precipitation sums of the Meteoservis sensor of $\leqslant$ 0.5 mm/5 min | 0.5 mm/5 min to 1.0 mm/5 min | $\geqslant$ 1.0 mm/5 min).

- The incorrect implementation of so called *maxchecklevels* was corrected. The idea is that only data that were not flagged up to a certain QC-layer, which is specified by the *maxchecklevel*, is used as a reference for a check. This concept was in principle already implemented in QCSv2. However, the implementation was incorrect for precipitation sums. As soon as any precipitation sum was available in the cache, this sum was reused by the checks, regardless of the *maxchecklevel*. This was rectified.

- A technical maximum value of the Friedrichs type rain gauges has been found in the technical specifications and is now used as QC-layer 2 upper boundary value. In QCSv2 an empirical value of 180 mm/5 min had been used. This value was changed to 150 mm/5 min. While this change has no significant consequences, it was done for consistency with the QC-layer 2 concept.

- Parts of the source code have been rewritten in order to include less execute commands. The actual check algorithms were not altered in this process, but the new version avoids a bug of the programming environment and improves the readability of the source code.

- Some minor bugs and weaknesses in the source code have been detected and corrected. An example was the temporarily incorrect implementation of the function *getReference*, which led to weaknesses in QC-layer 4. During this time the check of constancy was weakened and the check for too fast changes was always passed.

- Some minor bugs regarding the data portal were reported. An example are column displacements in the .csv files containing station data. Also an inconsistency in the visualization of the precipitation sums of different levels was discovered and subsequently corrected by the WegenerNet team.

5 Verification and Visualization of the Improvements

In this chapter the improvements done to the Quality Control System (QCS) are verified and visualized. First a method to compare the performance of the QCS versions on the basis of three key figures of merit was developed and applied to five case studies. Furthermore for each case study a visualization of the performance is given.

A second approach demonstrates the improvement based on seasonal precipitation sums. The examples for the improvement of processing speed were already presented in Section 4.4, Table 4.1.

5.1 Case Studies

Five case studies were done to verify and visualize the improvements of the QCS. The case studies include a short and heavy convective rainfall event (case 1), a long duration and very variable convective rainfall event (case 2), a medium duration and heavy convective rainfall event (case 3), a stratiform rainfall event (case 4) and a snowfall event (case 5). For each case study the analyzed period is the duration of the respective precipitation event plus 60 minutes, in order to include all effects of the 60 min checks towards the full end of the event. An exception is the snowfall event, where the whole day was analyzed.

Using *precipitation plots* (see Subsection 3.2.2), the rain gauges were divided into *bad rain gauges* and *good rain gauges*. *Bad rain gauges* are gauges that show a systematic error (i.e. a total or partial blockage). *Good rain gauges* are all rain gauges that are not bad rain gauges, including gauges with single wrong values or missing data (e.g. due to transmission problems). Based on this distinction, all data samples within the analyzed period were classified into one of the following five groups:

1. *Bad values at good rain gauges*: All samples from *good rain gauges* with a QF in QC-layer 1 or 2. A flag in QC-layer 1 indicates missing data, which contribute by far the largest part of samples of this type. Flags in QC-layer 2 indicate obviously wrong values and are rather rare. Since these layers are practically identical in QCSv2 and QCSv3, this group was not included in the further analysis.

2. *Good values at good rain gauges*: All samples from *good rain gauges* that do not belong to the above group. It includes mainly samples with no QFs and samples

with QFs in the QC-layers 4, 5 and 6, that were found to be unjustified. In this group are also some single deficient samples from otherwise working gauges.

3. *Bad values at bad rain gauges*: All obviously wrong measurements at *bad rain gauges*. They were defined according to visual reviews of precipitation plots of the analyzed period. While there is some uncertainty in classifying single samples as bad values, longer periods of obviously wrong measurements are easy to identify and thus the uncertainty reduces to defining the start and the stop time of such periods.

4. *Technical bad values*: All samples at totally blocked rain gauges after the local end of the precipitation event. While the measured values during this time are correct (no precipitation), the measurement procedure is still flawed. In QCSv3 these samples are flagged, while they were not flagged in QCSv2. In order to allow comparisons between the two QCS versions, these samples were assigned to an own group and not included in the further analysis. The local ends of the precipitation event were estimated using visual inspection of precipitation plots.

5. *Good values at bad rain gauges*: All samples at *bad rain gauges* that are neither bad values nor technical bad values. This includes all samples before the local start of a precipitation event and all samples from partially blocked gauges measuring no precipitation after the local end of the precipitation event.

Using this classification, the performance of the two QCS versions is compared on the basis of three figures of merit:

Detected bad values (DBV) The fraction of flagged bad values at *bad rain gauges*. DBV should be as large as possible, ideally 100 %.

False alarms at good rain gauges (FAg) The fraction of flagged good values at *good rain gauges*. FAg should be as low as possible, ideally 0 %.

False alarms at bad rain gauges (FAb) The Fraction of flagged good values at *bad rain gauges*. FAb also should be as low as possible, but it is of minor importance compared to FAg because there are comparatively few good values at *bad rain gauges* during the time periods of interest.

For each case study these figures of merit are given both total and broken down to the QC-layers 4, 5 and 6. Furthermore, the performance of QCSv2 and QCSv3 is visualized in a plot for each case study. The bad values and technical bad values of every *bad rain gauge* as well as the respective flags given by both QCSv2 and QCSv3 are plotted in a timeline plot.

5.1.1 Case Study 1—Short & Heavy Convective Rainfall

Case study 1 is a short duration, but heavy convective rainfall event on August 19, 2011 with a duration of about 1.5 hours and a maximum measured intensity of 14 mm/5 min. It is one of the precipitation events during which the climatological boundaries were exceeded in QCSv2 (see Subsection 3.2.2) and shows a medium spatial variability (compare Subsection 3.2.3). Using precipitation plots and time series of this event, no flushes, thirteen total blockages and two partial blockages were identified. Detailed information on the number of samples at *good rain gauges* and *bad rain gauges* is given in Table 5.1.

As shown in Table 5.2, there was an improvement of all three figures of merit, the DBV value increased from 70.7 % to 91.4 %. FAg and FAb decreased from 4.5 % to 1.7 % and from 12.9 % to 7.8 %, respectively. As expected, these results are mainly due to the improvement of QC-layer 6. Figure 5.1 shows that especially the handling of partial blockages improved significantly.

Table 5.1: General information on case study 1.

Precipitation event	Aug. 19, 2011 13:25-14:45 UTC
Analyzed period	Aug. 19, 2011 13:25-15:45 UTC
Samples per rain gauge	29
Number of rain gauges (Good/Bad/Total)	137/15/152
Samples at good rain gauges (Good values/Bad values/Total)	3972/1/3973
Samples at bad rain gauges (Good val./Bad val./Tech. bad val./Total)	84/116/235/435
Total number of data samples	4408

Table 5.2: Detected bad values (DBV), false alarms at good rain gauges (FAg) and false alarms at bad rain gauges (FAb) of QCSv2 and QCSv3, for case study 1.

	DBV		**FAg**		**FAb**	
	QCSv2	QCSv3	QCSv2	QCSv3	QCSv2	QCSv3
All levels	70.7%	91.4%	4.6%	1.7%	12.9%	7.8%
Level 6	68.1%	87.9%	4.5%	1.7%	12.9%	7.8%
Level 5	6.0%	6.0%	0%	0%	0%	0%
Level 4	0%	0%	0.1%	0%	0%	0%

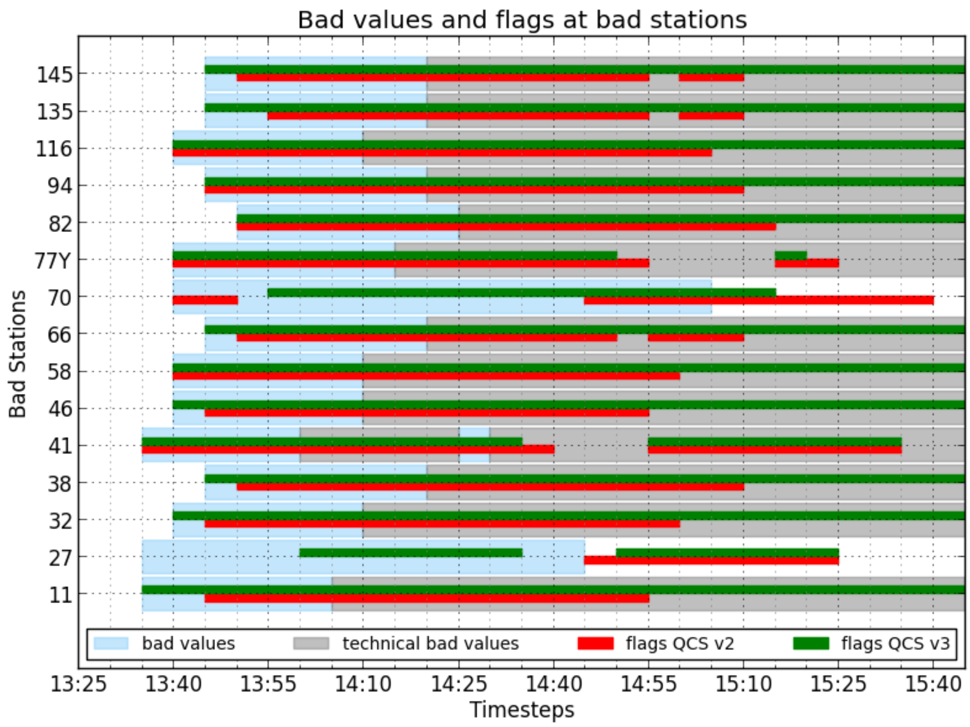

Figure 5.1: Bad values, technical bad values and flags given by QCSv2 and QCSv3 at bad rain gauges, for case study 1.

5.1.2 Case Study 2—Long & Variable Convective Rainfall

Case study 2 is a long-duration convective rainfall event on April 05, 2012. Its maximum measured intensity of 6.8 mm/5 min exceeded the April climatological boundary in QCSv2. Compared to case study 1, it shows a higher spatial variability and has a much longer duration, of about 7 hours. Only two partial blockages were identified. Detailed information on the number of samples at good and bad rain gauges is given in Table 5.3.

As shown in Table 5.4, there was an improvement of all three figures of merit. The DBV increased from 66.1 % to 75.0 %. FAg and FAb decreased from 3.3 % to 2.0 % and from 32.1 % to 28.6 %, respectively. Again these results are mainly due to the improvement of QC-layer 6. As visualized in Figure 5.2, the handling of one partial blockage was slightly improved, while the other partial blockage is still handled imperfectly.

Table 5.3: General information on case study 2.

Precipitation event	Apr. 05, 2012 12:20-19:40 UTC
Analyzed period	Apr. 05, 2012 12:20-20:40 UTC
Samples per rain gauge	101
Number of rain gauges (Good/Bad/Total)	150/2/152
Samples at good rain gauges (Good values/Bad values/Total)	15043/107/15150
Samples at bad rain gauges (Good val./Bad val./Tech. bad val./Total)	146/56/0/202
Total number of data samples	15352

Table 5.4: Detected bad values (DBV), false alarms at good rain gauges (FAg) and false alarms at bad rain gauges (FAb) of QCSv2 and QCSv3, for case study 2.

	DBV		**FAg**		**FAb**	
	QCSv2	QCSv3	QCSv2	QCSv3	QCSv2	QCSv3
All levels	66.1%	75.0%	3.3%	2.0%	32.1%	28.6%
Level 6	66.1%	75.0%	3.3%	2.0%	32.1%	28.6%
Level 5	0%	0%	0%	0%	0%	0%
Level 4	0%	0%	0.1%	0%	0%	0%

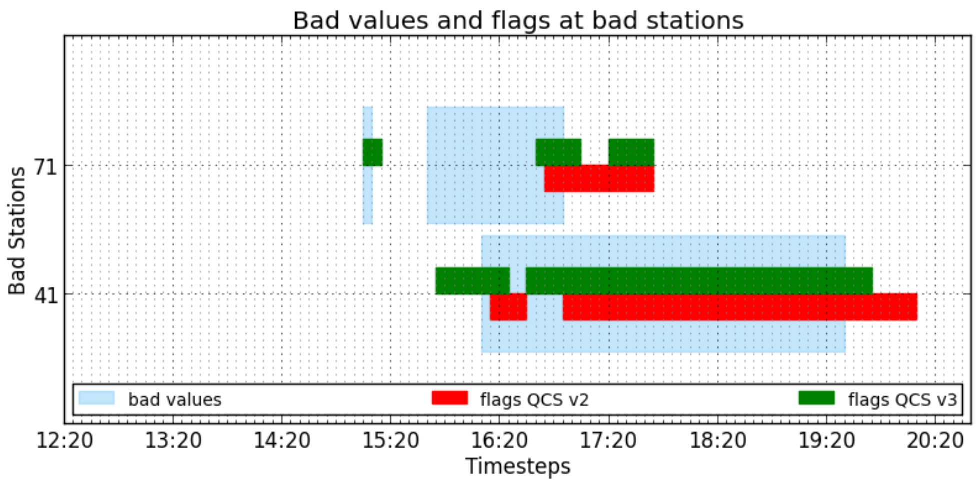

Figure 5.2: Bad values, technical bad values and flags given by QCSv2 and QCSv3 at bad rain gauges, for case study 2.

5.1.3 Case Study 3—Medium & Heavy Convective Rainfall

Case study 3 is medium duration heavy convective rainfall event that took place on August 03, 2011. Regarding the spatial variability, the duration of about 3 hours and the maximum intensity of 10 mm/5 min it is somewhere in the middle of the case studies 1 and 2. With eleven total blockages and six partial blockages, it is the case study with the most bad rain gauges. Detailed information on the number of samples at good and bad rain gauges is given in Table 5.5.

As shown in Table 5.6, there was an improvement of all three figures of merit. The DBV increased from 55.3 % to 71.6 %. FAg and FAb decreased from 4.5 % to 1.9 % and from 17.8 % to 13.4 %, respectively. Again these results are mainly due to the improvement of QC-layer 6. A visualization of the differences between QCSv2 and QCSv3 is given in Figure 5.3.

Table 5.5: General information on case study 3.

Precipitation event	Aug. 03, 2011 20:55 - Aug. 04, 2011 00:10 UTC
Analyzed period	Aug. 03, 2011 20:55 - Aug. 04, 2011 01:10 UTC
Samples per rain gauge	52
Number of rain gauges (Good/Bad/Total)	135/17/152
Samples at good rain gauges (Good values/Bad values/Total)	7020/0/7020
Samples at bad rain gauges (Good val./Bad val./Tech. bad val./Total)	220/320/344/884
Total number of data samples	7904

Table 5.6: Detected bad values (DBV), false alarms at good rain gauges (FAg) and false alarms at bad rain gauges (FAb) of QCSv2 and QCSv3, for case study 3.

	DBV		**FAg**		**FAb**	
	QCSv2	QCSv3	QCSv2	QCSv3	QCSv2	QCSv3
All levels	55.3%	71.6%	4.5%	1.9%	17.8%	13.4%
Level 6	55.3%	71.6%	4.5%	1.9%	17.8%	13.4%
Level 5	0%	0%	0.1%	0.1%	0%	0%
Level 4	0%	0%	0%	0%	0%	0%

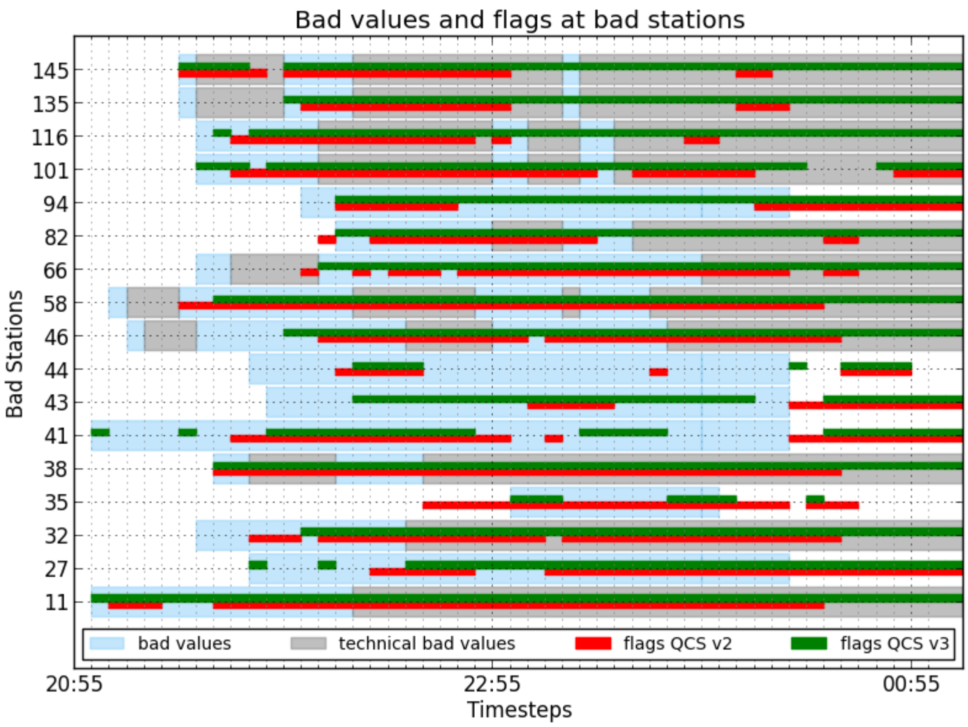

Figure 5.3: Bad values, technical bad values and flags given by QCSv2 and QCSv3 at bad rain gauges, for case study 3.

5.1.4 Case Study 4—Stratiform Rainfall

Case study 4 is a stratiform rainfall event on October 07, 2011 that lasted about 11 hours. It is characterized by a low spatial variability and comparatively low intensities. During the first 1.5 hours intensities up to 4.6 mm/5 min were measured, afterwards the intensities were well below 1 mm/5 min. There were eight total and three partial blockages identified. Detailed information on the number of samples at good and bad rain gauges is given in Table 5.7.

As shown in Table 5.8, the DBV slightly increased from 93.9 % to 94.7 % and the FAb decreased from 11.3 % to 7.7 %. Due to weaknesses of the partial blockage check related to very low intensities, the FAg increased from 3.7 % to 6.2 %. This, however, has only a minor impact on the Level 2 data quality, because due to the very low spatial variability and the low intensities, the interpolation of these values in the DPG is nevertheless rather good. A visualization of the differences between QCSv2 and QCSv3 is given in Figure 5.4.

Table 5.7: General information on case study 4.

Precipitation event	Oct. 07, 2011 05:10-16:20 UTC
Analyzed period	Oct. 07, 2011 05:10-17:20 UTC
Samples per rain gauge	147
Number of rain gauges (Good/Bad/Total)	141/11/152
Samples at good rain gauges (Good values/Bad values/Total)	20428/299/20727
Samples at bad rain gauges (Good val./Bad val./Tech. bad val./Tot.)	322/1079/216/1617
Total number of data samples	22344

Table 5.8: Detected bad values (DBV), false alarms at good rain gauges (FAg) and false alarms at bad rain gauges (FAb) of QCSv2 and QCSv3, for case study 4.

	DBV		**FAg**		**FAb**	
	QCSv2	QCSv3	QCSv2	QCSv3	QCSv2	QCSv3
All levels	93.9%	94.7%	3.7%	6.2%	11.3%	7.7%
Level 6	93.9%	94.7%	3.7%	6.2%	11.3%	7.7%
Level 5	0%	0%	<0.01%	<0.01%	0%	0%
Level 4	0%	0%	0%	0%	0%	0%

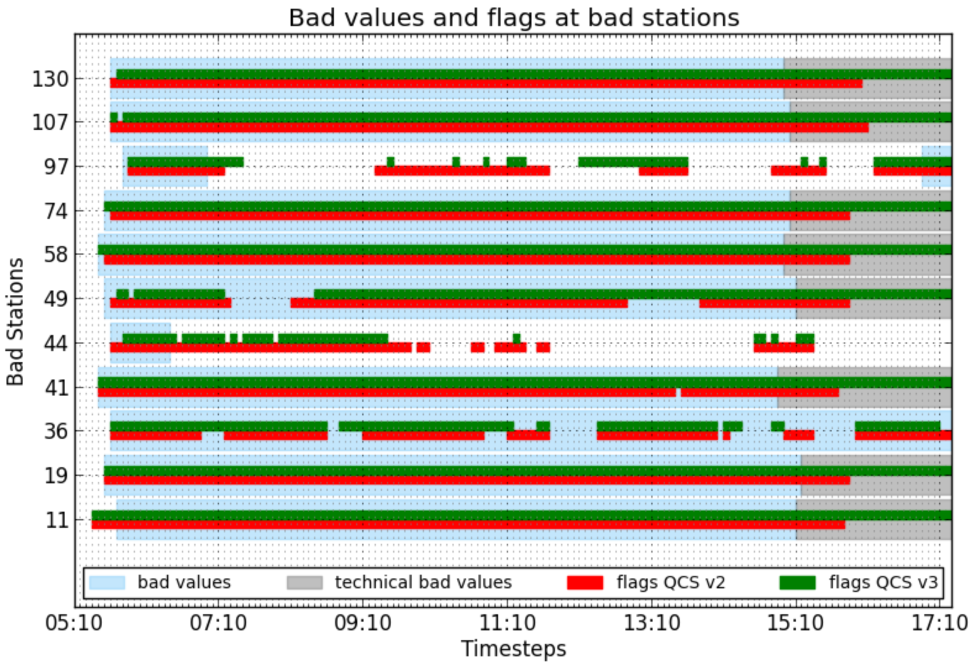

Figure 5.4: Bad values, technical bad values and flags given by QCSv2 and QCSv3 at bad rain gauges, for case study 4.

5.1.5 Case Study 5—Snowfall Event

Case study 5 is a snowfall event on January 16, 2013. It was already discussed to some extent in Subsection 3.3.2. During this event only three heated gauges were operating properly. Due to this the exact start and stop time of the event could not be identified and the whole day was analyzed. The daily precipitation sum measured at the heated gauges ranges from 11.7 mm to 22.5 mm.

When defining bad rain gauges and bad values some simplifications were done. The three heated gauges were defined to be good rain gauges and all unheated or malfunctioning heated rain gauges were defined to be bad rain gauges. While there were some measurements around noon when the air temperature exceeded 2 °C, all samples from the bad rain gauges were defined to be bad values. Detailed information on the number of samples at good and bad rain gauges is given in Table 5.9.

As shown in Table 5.10, nearly all (97.3 %) measurements at unheated rain gauges were flagged in QCSv3, compared to 3.7 % in QCSv2. The fact that not all unheated gauges are flagged in QCSv3 is due to the simplifications given above. Also there were no values from heated stations incorrectly flagged in QCSv3, while 13.3 % were incorrectly flagged in QCSv2.

For snowfall events the improvement can be better visualized by comparing Level 2 grid data that were interpolated from Level 1 data of the different QCS versions. Unfortunately for this case study, there are too few good gauges to interpolate to the grid data. Therefore an example from a similar snowfall event on January 24, 2007 is given in Figure 5.5, which well illustrates the improvement by QCSv3.

Table 5.9: General information on case study 5.

Analyzed period	Jan. 16, 2013 00:00-23:55 UTC
Samples per rain gauge	288
Number of rain gauges (Good/Bad/Total)	3/149/152
Samples at good rain gauges (Good values/Bad values/Total)	864/0/864
Samples at bad rain gauges (Good val./Bad val./Tech. bad val./Total)	0/42912/0/42912
Total number of data samples	43776

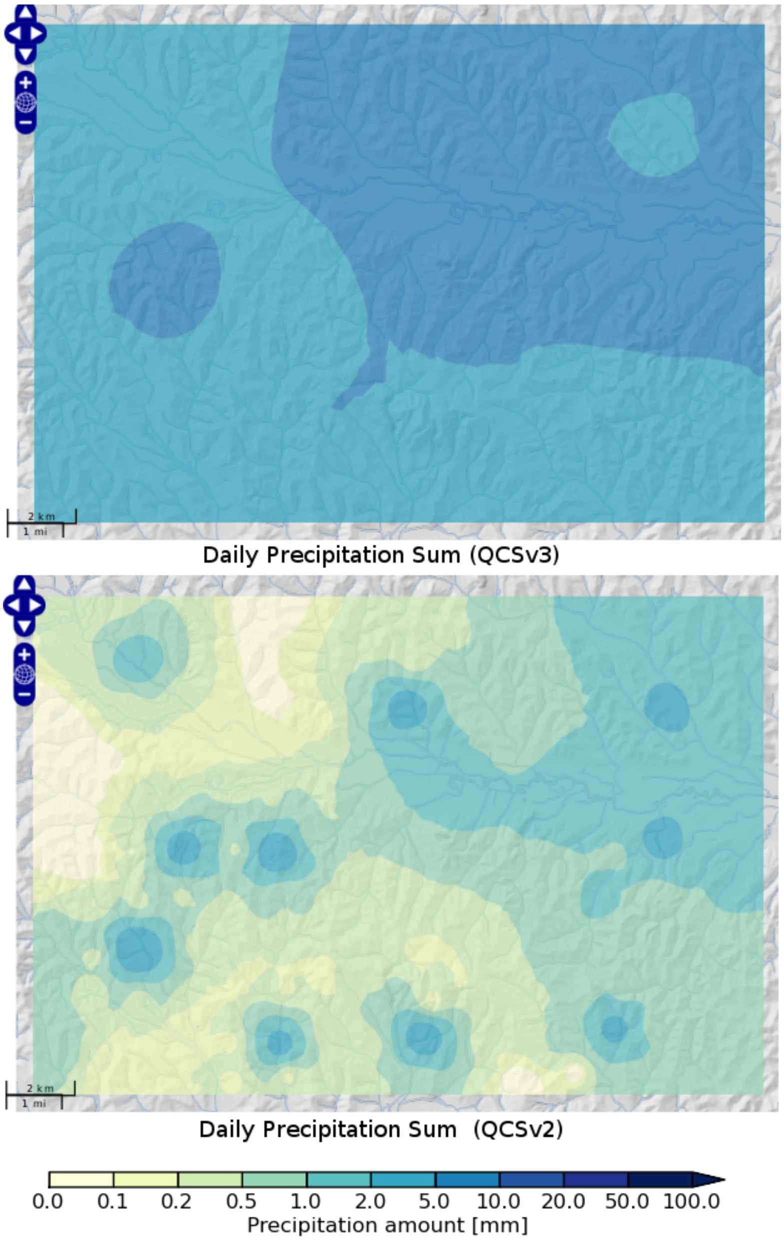

Figure 5.5: Precipitation sum from January 24, 2007 06:00 to January 25, 2007 06:00 UTC containing an exemplary Snowfall event. Level 2 grid data interpolated from QCSv2 (lower) and QCSv3 (upper).

Table 5.10: Detected bad values (DBV), false alarms at good rain gauges (FAg) and false alarms at bad rain gauges (FAb) of QCSv2 and QCSv3, for case study 5.

	DBV		**FAg**		**FAb**	
	QCSv2	QCSv3	QCSv2	QCSv3	QCSv2	QCSv3
All levels	3.7%	97.3%	13.3%	0%	0%	0%
Level 6	0.4%	0%	13.1%	0%	0%	0%
Level 5	3.5%	97.3%	4.6%	0%	0%	0%
Level 4	0%	0%	0%	0%	0%	0%

5.2 Comparison of Climatological Precipitation Sums

Another approach to verify the improvement of data quality is, finally, based on the comparison of station-averaged seasonal precipitation sums. The basic idea is that Level 2 data are very likely underestimating the real precipitation sums and therefore increased sums indicate an improvement of data quality. Compared are:

- Level 0 data (sums derived directly from Level 0 data),
- Level 2 V3 data (sums generated by the DPG from QCSv2-processed data),
- Level 2 V4 data (sums generated by the DPG from QCSv3-processed data),

for the periods December 2010 to February 2011 (DJF), March to May 2011 (MAM), June to August 2011 (JJA), and September to November 2011 (SON), respectively.

The precipitation sums were averaged over all WegenerNet stations, except for the season DJF, where just the average of the three then operational heated gauges is used. This was necessary because due to the small number of operational heated gauges, and therefore the lack of correct data, the values at the unheated stations could not be reasonably interpolated.

In all likelihood, the Level 0 data sums underestimate the real precipitation amount because contributions to a positive bias could only originate from flushes, corrupted data files and systematic measurement errors of the rain gauges. It is reasonable to assume that contributions from flushes and corrupted data to seasonal sums are negligibly small and that the average systematic measurement error is negative (see Szeberenyi 2014). On the other hand missing data and blockages can introduce a considerable negative bias to Level 0 data.

In Level 2 data this negative bias should have been corrected by the flagging and interpolation of missing or bad values in the QCS and the DPG (except for the bias from systematic measurement errors). A comparison of Level 0 and Level 2 data showed, however, that the bias is only marginally corrected. Sometimes Level 2 data sums are even lower than Level 0 data sums, in which case the underestimation is obvious.

Table 5.11: Station-averaged seasonal precipitation sums in Level 0 data, Level 2 V3 data (value and ratio to Level 0 data) and Level 2 V4 data (value and ratio to Level 0 data), and relative difference of Level 2 V3 and Level 2 V4 data, for the year 2011 (DJF 2010/2011).

Period	**Level 0**	**Level 2 V3**		**Level 2 V4**		**Rel. Diff.**
	[mm]	[mm]	% of Level 0	[mm]	% of Level 0	
DJF	69.9	55.2	79.0 %	75.9	108.5 %	37.3 %
MAM	149.0	144.4	96.9 %	146.1	98.1 %	1.24 %
JJA	293.1	285.7	97.5 %	295.0	100.7 %	3.28 %
SON	156.4	160.6	102.7 %	162.2	103.7 %	0.97 %
Sum	668.3	645.0	96.6 %	679.2	105.2 %	5.2 %

An existing underestimation of Level 2 data is backed by the results of Szeberenyi (2014), who compared Level 2 monthly area mean precipitation sums to measurements of the Meteoservis rain gauge at the reference station. According to her analysis the mean relative difference for the period from summer 2008 to winter 2012/2013 is about −24.5 % (±16.5 %), in winter even up to −45.6 % (±9.9 %).

The results are given in Table 5.11 and clearly point out that the improvements implemented in the QCS resulted in a decreased underestimation of climatological precipitation sums and therefore an improved data quality. While Level 2 V3 data show an obvious underestimation in DJF, MAM and JJA, Level 2 V4 data do so only in MAM. Particularly large is the improvement in DJF, where the Level 2 V4 data sum is 37.3% larger than the Level 2 V3 data sum. In MAM and JJA the increase in the Level 2 data sum amounted to 1.24% and 3.28%, respectively. The lowest increase is evident in autumn (+0.97 %), where already the Level 2 V3 data sum was larger than the Level 0 data sum. The annual precipitation sum in Level 2 data increased by 5.2% and is now about 5% larger than the Level 0 data sum instead of 5% lower, which well indicates an overall improvement.

6 Summary and Conclusions

The purpose of this MSc thesis was to improve the performance of the WegenerNet Quality Control System (QCS) and thereby improve the quality of the final data products generated by the WegenerNet. The approach was to first identify weaknesses and then to modify the concerned parts of the QCS in order to improve them, with a focus on precipitation measurements.

After an introduction to the WegenerNet, a statistical analysis of the quality flags given so far was done and this confirmed the presumed importance of the quality control of precipitation measurements. Case studies revealed a potential for improvement in the following areas: First, several climatological boundary values and the parameters of the interstational check were somewhat too strict. Second, an analysis of the performance of the QCS when confronted with typical rain gauge malfunctions indicated weaknesses in the detection of blockages. Lastly, the handling of snowfall events was inadequate.

In order to mitigate these weaknesses, the concerned bounds and check parameters were revised and several snowfall-related algorithms were improved. A new concept for the interstational comparison of precipitation data was developed, which basically consisted of the introduction of several new checks, each tailored to detect a specific typical rain gauge malfunction. Furthermore the processing speed of the QCS was sped up by about 40 %.

A verification and visualization of the improvements was done on the basis of five case studies and suggested that a considerable improvement of precipitation data quality has been achieved. Overall the number of detected bad values increased and the number of false alarms decreased. This is especially true for convective rainfall events. Only for stratiform low-intensity rainfall a slight increase of false alarms is evident, which is not really important in practice because of the relatively easy spatial interpolation during such events. Also the improved handling of snowfall events was verified by a case study. Furthermore, a comparison of seasonal precipitation sums confirmed the improved quality for climatological sums.

The issue of snow that is accumulated on unheated rain gauges and - when melting - is being interpreted as rainfall has not been solved within this thesis. Although the detection of such events is relatively simple (since associated with an unusually high number of “total blockages” at heated gauges), the design of the QCS does not allow the straight-forward implementation of such a check. It is, however, considered to introduce additional quality control procedures based on checking longer time periods. A check on, for example, daily precipitation sums against thresholds and neighbor station values would improve the detection of minor blockages during short low intensity rainfall events. Within this new framework also the check for melting snow could possibly be realized more easily.

Further potential improvements include the introduction of additional intrastational checks, e. g. precipitation versus soil moisture (sensors have been recently installed), as well as a further differentiation of the check algorithms, parameters and boundary values according to month and precipitation type. Also an evaluation and subsequent calibration of climatological precipitation sums seems reasonable. Since this MSc thesis mostly focused on precipitation, the other measured parameters were not analyzed in greater depth. Especially an evaluation of the wind and soil parameters could reveal further fields of potential improvement.

The present QCS improvement work has clearly benefited the WegenerNet precipitation data quality available to users, which is encouraging for further updates as outlined above.

Appendix — Tables QCS Rules and Boundary Values

Table 1: List of QCS layers and rules

QC-layer	Rule	Check	Note
0	0	**Operations check**	manual flagging
1	0	**Availability check**	create fail values for missing data
2		**Sensor check**	technical specifications
	0	min	
	1	max	
3		**Climatological check**	monthly boundaries
	0	min	
	1	max	
4		**Time variability check**	
	0	time gradient check min	too fast changes, negative gradient
	1	time gradient check max	too fast changes, positive gradient
	2	time constancy check	implausible constancy
5		**Intrastational check**	
	2	tempPrec check	unheated rain gauges when $T < 2\,°\mathrm{C}$
	4	refPrec check	compare rain gauge models
	5	windsensor check	check for fail values
	6	windmeanBoe check	flag if peak gust < wind mean
	7	windvalues check	flag if wind mean speed == peak gust and wind mean dir. == peak gust dir.
	8	windboeBoedir check	check for fail values
6		**Interstational check**	
	0	maxdiff check	unnamed in QCSv2
	1	flush check	only QCSv3
	2	total blockage check	only QCSv3
	3	partial blockage check	only QCSv3
	4	fade away check	only QCSv3
7	0	**External reference check**	compare to ZAMG data

Table 2: QCS layer 2 boundaries in QCSv2

Parameter	**Min value**	**Max value**
Air temperature	−40 °C	123.8 °C
Relative humidity	1 %	104 %
Precipitation (Friedrichs)	0 mm/10 min	180 mm/10 min
Precipitation (Young)	0 mm/10 min	240 mm/10 min
Precipitation (Kroneis)	0 mm/10 min	240 mm/10 min
Wind direction	0°	360°
Wind speed	$0\,m\,s^{-1}$	$60\,m\,s^{-1}$
Peak gust	$0\,m\,s^{-1}$	$60\,m\,s^{-1}$
Peak gust direction	0°	360°
Soil temperature (Geoprecision)	−40 °C	120 °C
pF-value (Geoprecision)	0	7
Air pressure	825 hPa	1050 hPa
Net radiation	$-990\,W\,m^{-2}$	$2000\,W\,m^{-2}$

Table 3: QCS layer 2 boundaries in QCSv3

Parameter	**Min value**	**Max value**
Air temperature	−40 °C	123.8 °C
Relative humidity	1 %	104 %
Precipitation (Friedrichs)	0 mm/10 min	150 mm/10 min
Precipitation (Young)	0 mm/10 min	240 mm/10 min
Precipitation (Kroneis)	0 mm/10 min	240 mm/10 min
Wind direction	0°	360°
Wind speed	$0\,m\,s^{-1}$	$60\,m\,s^{-1}$
Peak gust	$0\,m\,s^{-1}$	$60\,m\,s^{-1}$
Peak gust direction	0°	360°
Soil temperature (Geoprecision)	−40 °C	120 °C
pF-value (Geoprecision)	0	7
Soil temperature (Stevens)	−10 °C	55 °C
Soil moisture (Stevens)	$0\,m^3\,m^{-3}$	$1.03\,m^3\,m^{-3}$
Soil el. conductivity (Stevens)	$0.01\,S\,m^{-1}$	$1.51\,S\,m^{-1}$
Diode temperature (Stevens)	−10 °C	55 °C
Air pressure	825 hPa	1050 hPa
Net radiation	$-990\,W\,m^{-2}$	$2000\,W\,m^{-2}$

Table 4: QCS layer 3 boundaries in QCSv2 and QCSv3

Parameter	**Month**	**Min value**	**Max value**
Air temperature	1	−29 °C	23 °C
	2	−26 °C	26 °C
	3	−25 °C	30 °C
	4	−11 °C	33 °C
	5	−8 °C	37 °C
	6	−4 °C	39 °C
	7	−2 °C	41 °C
	8	−1 °C	43 °C
	9	−7 °C	37 °C
	10	−13 °C	32 °C
	11	−22 °C	27 °C
	12	−25 °C	23 °C
Relative humidity (QCSv2)	1-12	20 %	104 %
Relative humidity (QCSv3)	1-12	10 %	104 %
Wind speed	1	$0\,m\,s^{-1}$	$21\,m\,s^{-1}$
	2	$0\,m\,s^{-1}$	$20\,m\,s^{-1}$
	3	$0\,m\,s^{-1}$	$21\,m\,s^{-1}$
	4	$0\,m\,s^{-1}$	$20\,m\,s^{-1}$
	5	$0\,m\,s^{-1}$	$19\,m\,s^{-1}$
	6	$0\,m\,s^{-1}$	$21\,m\,s^{-1}$
	7	$0\,m\,s^{-1}$	$19\,m\,s^{-1}$
	8	$0\,m\,s^{-1}$	$27\,m\,s^{-1}$
	9	$0\,m\,s^{-1}$	$17\,m\,s^{-1}$
	10	$0\,m\,s^{-1}$	$23\,m\,s^{-1}$
	11	$0\,m\,s^{-1}$	$20\,m\,s^{-1}$
	12	$0\,m\,s^{-1}$	$23\,m\,s^{-1}$
Peak gust	1-12	$0\,m\,s^{-1}$	$55.6\,m\,s^{-1}$
Soil temperature (Geoprecision)	1	−4 °C	11 °C
	2	−4 °C	11 °C
	3	−3 °C	16 °C
	4	1 °C	20 °C
	5	7 °C	26 °C
	6	8 °C	29 °C
	7	13 °C	32 °C
	8	13 °C	37 °C
	9	6 °C	25 °C
	10	3 °C	22 °C
	11	−1 °C	17 °C
	12	−3 °C	12 °C
pF-value (Geoprecision)	1-12	0	7
Soil moisture (Stevens; in QCSv3)	1-12	$0.05\,m^3\,m^{-3}$	$0.75\,m^3\,m^{-3}$
Air pressure	1-12	930 hPa	1015 hPa
Net radiation	1-12	$-300\,W\,m^{-2}$	$1000\,W\,m^{-2}$

Table 5: QCS layer 4 boundaries (time gradient check) in QCSv2

Parameter	Month	Max value	Min value
Air temperature	1-12	10 °C	−10 °C
Relative humidity	1-12	30 %	−30 %
Precipitation	1	4 mm/10 min	0 mm/10 min
	2	5 mm/10 min	0 mm/10 min
	3	7 mm/10 min	0 mm/10 min
	4	9 mm/10 min	0 mm/10 min
	5	22 mm/10 min	0 mm/10 min
	6	35 mm/10 min	0 mm/10 min
	7	20 mm/10 min	0 mm/10 min
	8	25 mm/10 min	0 mm/10 min
	9	34 mm/10 min	0 mm/10 min
	10	19 mm/10 min	0 mm/10 min
	11	10 mm/10 min	0 mm/10 min
	12	17 mm/10 min	0 mm/10 min
Soil temperature (Geoprecision)	1-12	0.12 °C	−0.12 °C
pF-value (Geoprecision)	1-12	1	-1
Air pressure	1-12	3 hPa	−3 hPa
Net radiation (day)	1-12	$1000\,W\,m^{-2}$	$-1000\,W\,m^{-2}$
Net radiation (night)	1-12	$100\,W\,m^{-2}$	$-100\,W\,m^{-2}$

Table 6: QCS layer 4 boundaries (time gradient check) in QCSv3

Parameter	Month	Max value	Min value
Air temperature	1-12	10 °C	−10 °C
Relative humidity	1-12	30 %	−30 %
Precipitation	1	15 mm/10 min	0 mm/10 min
	2	15 mm/10 min	0 mm/10 min
	3	15 mm/10 min	0 mm/10 min
	4	20 mm/10 min	0 mm/10 min
	5	27 mm/10 min	0 mm/10 min
	6	35 mm/10 min	0 mm/10 min
	7	33 mm/10 min	0 mm/10 min
	8	33 mm/10 min	0 mm/10 min
	9	35 mm/10 min	0 mm/10 min
	10	27 mm/10 min	0 mm/10 min
	11	20 mm/10 min	0 mm/10 min
	12	20 mm/10 min	0 mm/10 min
Soil temperature (Geoprecision)	1-12	0.12 °C	−0.12 °C
pF-value (Geoprecision)	1-12	0.5	-0.5
Soil temperature (Stevens)	1-12	0.42 °C	−0.42 °C
Soil moisture (Stevens)	1-12	$0.1\,m^3\,m^{-3}$	$-0.1\,m^3\,m^{-3}$
Air pressure	1-12	3 hPa	−3 hPa
Net radiation (day)	1-12	$1000\,W\,m^{-2}$	$-1000\,W\,m^{-2}$
Net radiation (night)	1-12	$100\,W\,m^{-2}$	$-100\,W\,m^{-2}$

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Abstract:
The WegenerNet is a network of 151 meteorological stations covering an area of about 20×15 km in the south-east of Austria and providing near real time data with a resolution of five minutes. The data quality is ensured by a variety of procedures and checks, which are subsumed and automated in the Quality Control System (QCS).
The objective of this thesis was to evaluate and improve the QCS with focus on precipitation data. The evaluation included a statistical analysis backing the focus on precipitation, tests of the validity of several climatological thresholds and check parameters and an assessment of the performance of the QCS when confronted with typical rain gauge malfunctions and with snowfall events. Main areas of improvement were revisions of climatological thresholds, the correction of some inadequate algorithms related to snowfall events and a redesign of the interstational comparison of precipitation data. The parameters of the existing interstational check were revised and four new interstational checks, each tailored to a specific rain gauge malfunction, were implemented.
A verification of the improvements was done on the basis of five case studies. The results show a significantly increased number of detected bad values as well as a reduction of false alarms for three convective rainfall events of varying length and intensity. The handling of stratiform rainfall events had been already relatively good in the existing QCS version and a case study therefore did not show much change. A fifth case study confirmed the improved handling of snowfall events. Furthermore, an analysis of the seasonal precipitation sums in 2011 indicated a decreased underestimation of climatological precipitation sums. Overall the QCS upgrades clearly benefited the data quality available to users.

Zum Inhalt:
Das WegenerNet ist ein Netzwerk von 151 meteorologischen Stationen im Südosten Österreichs, das für ein Gebiet von etwa 20×15 km Messwerte mit einer zeitlichen Auflösung von fünf Minuten liefert. Die Datenqualität wird durch eine Reihe von Plausibilitätsprüfungen sichergestellt, welche im Quality Control System (QCS) zusammengefasst und automatisiert durchgeführt werden.
Das Ziel der vorliegenden Masterarbeit war die Evaluierung und Verbesserung des QCS, mit Schwerpunkt auf der Qualitätskontrolle von Niederschlagsdaten. Die Evaluierung umfasste eine statistische Analyse der bisher als fehlerhaft markierten Daten, die Überprüfung einiger verwendeter Parameter sowie eine Analyse der Leistungsfähigkeit des QCS bei Auftreten typischer Fehlfunktionen der Niederschlagsgeber und bei Schneefallereignissen.
Auf Basis der Ergebnisse wurde eine Reihe von Modifikationen am QCS durchgeführt. Insbesondere waren dies die Ausweitung klimatologischer Grenzwerte, die Korrektur einiger bei Schneefall inadäquater Algorithmen, die Überarbeitung des Interstations–Vergleichs von Niederschlagssummen, sowie die Einführung zusätzlicher Vergleichstests, die auf typische Fehlfunktionen der Niederschlagsgeber spezialisiert sind.
Die Verbesserung der Datenqualität wurde anhand von fünf Fallstudien überprüft. Für konvektiven Niederschlag zeigte sich eine erheblich verbesserte Detektion fehlerhafter Werte bei gleichzeitiger Abnahme von fälschlich als problematisch markierten Werten. Bei stratiformem Niederschlag war die Leistung des QCS schon vor den Modifikationen gut und es gab daher keine wesentlichen Änderungen. Die verbesserte Vorgangsweise bei Schneefall wurde bestätigt und eine Analyse der saisonalen Niederschlagssummen im Jahr 2011 deutete auf eine nun geringere Unterschätzung dieser Summen hin. Insgesamt liefert das QCS nun eindeutig verbesserte Datenqualität an die NutzerInnen.

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