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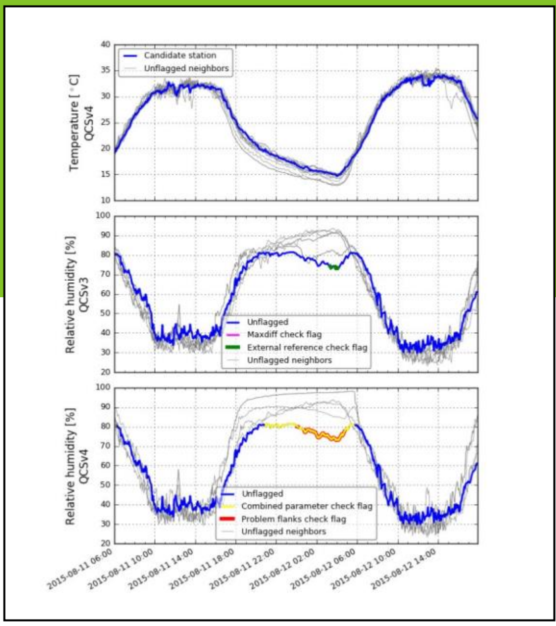


Scientific Report No. 74-2017

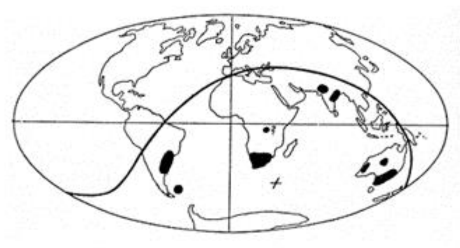
Analysis of the Quality of WegenerNet Humidity Data and Improvements

Daniel Scheidl, Jürgen Fuchsberger,
and Gottfried Kirchengast

December 2017

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 informationen at www.wegcenter.at)

The present report is the result of a Wegener Center research project completed in June 2017. The work was funded 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).

Wegener Center Verlag • Graz, Austria

ISBN 978-3-9504501-2-5

December 2017

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Abstract

The WegenerNet Feldbach Region is a network of 154 meteorological stations (status December 2017), providing data with a temporal resolution of five minutes and a spatial resolution of about 1.4 km. The data quality is ensured by a number of automatized quality checks, subsumed in the Quality Control System (QCS).

In this work distinctive malfunctions of the relative humidity sensors of the WegenerNet are addressed. The sensors frequently showed episodes of problematic behavior, during which values above a certain threshold were truncated or showed "inverse behavior". Until now, the detection of problem behavior was largely dependent on manual inspection because it was not adequately recognized by the QCS. The objective of this work was to analyze this problem behavior and to improve the procedures and QCS algorithms, such that problem behavior is automatically identified.

The main approach was to set up a criterion for problematic humidity values based on an interstational comparison of relative humidity and air temperature.

First, this criterion was embedded into an algorithm to automatically identify problem sensors on a daily basis. A verification revealed that the algorithm is more reliable and more accurate than manual inspection.

Then the criterion was implemented in the QCS to check individual humidity values. Additionally, some further improvements of the QCS were done, including another quality check based on the characteristic temporal evolution of problem behavior. Case studies and a statistical analysis verified that the new QCS version has an improved detection of problematic values, while producing less false alarms.

Zusammenfassung

Das WegenerNet Region Feldbach ist ein Netzwerk von 154 meteorologischen Stationen (Stand Dezember 2017), das Daten mit einer zeitlichen Auflösung von fünf Minuten und einer räumlichen Auflösung von ca. 1.4 km liefert. Die Datenqualität wird durch verschiedene automatisierte Plausibilitätsprüfungen gewährleistet, die im Quality Control System (QCS) zusammengefasst sind.

Die vorliegende Arbeit befasst sich mit der Erkennung des Problemverhaltes der WegenerNet Feuchtesensoren. Die Sensoren zeigten häufig Episoden von problematischem Verhalten, bei denen Werte oberhalb einer bestimmten Schwelle abgeschnitten wurden oder sogar „inverses Verhalten“ auftrat. Bisher war die Erkennung solchen Problemverhaltens weitgehend von einer manuellen Überprüfung abhängig, da es vom QCS nicht adäquat detektiert wurde. Ziel dieser Arbeit war es, das Problemverhalten zu analysieren und die Verfahren und QCS-Algorithmen so zu verbessern, dass das Problemverhalten automatisch erkannt und falsche Werte im QCS identifiziert werden.

Dazu wurde ein Kriterium aufgestellt, das problematische Feuchtigkeitswerte durch einen Vergleich der relativen Feuchte und der Lufttemperatur mit Nachbarstationen erkennen soll. Dieses Kriterium wurde in einen Algorithmus eingebettet, der anhand der Daten eines Tages bewertet ob Problemverhalten an einem Sensor vorliegt. Eine Auswertung ergab, dass dieser Algorithmus zuverlässiger und genauer ist als die bisherige manuelle Sichtung.

Daher wurde das Kriterium in einen QCS-Test implementiert, wo es auf einzelne Feuchtewerte angewandt wird. Darüber hinaus wurden einige andere Verbesserungen des QCS durchgeführt. Unter anderem wurde ein weiterer Test implementiert, der sich die charakteristische zeitliche Entwicklung des Problemverhaltens zunutze macht. Einige Fallstudien und eine statistische Analyse bestätigten, dass die neue QCS-Version das Problemverhalten besser erkennt und gleichzeitig weniger falsche Alarme liefert.

Contents

1 Introduction **7**

2 The WegenerNet and its Quality Control System **9**
2.1 The WegenerNet Climate Station Network 9
2.2 The Quality Control System of the WegenerNet 11

3 Characterization of Relative Humidity Problem Sensor Behavior **13**
3.1 Relative Humidity Problem Behavior 13
3.2 Case Studies of Sensors Showing Problem Behavior 14
3.2.1 Case Study – Station 20: Evolving Problem Behavior 14
3.2.2 Case Study – Station 87: Sudden Problem Occurrence and Recovery 14
3.3 Analysis of Different Humidity Parameters during Problem Behavior . . . 17

4 Definition of a Criterion for Problematic Humidity Values **19**
4.1 Extended Neighborhood Levels 19
4.2 Definition of the Problem Behavior Criterion 20
4.3 Derivation of the Problem Behavior Criterion 21
4.3.1 Comparison of Good and Problem Sensor Diagnose Plots 21
4.3.2 Dependence on Location Class and Season 25

5 Automatic Problem Sensor Status Identification **27**
5.1 Implementation into (Re-)Processing Routines 27
5.2 Algorithm Description 27
5.3 Verification Results 29

6 Improvements of the Quality Control System **34**
6.1 Implementation into (Re-)Processing Routines 34
6.2 New Check: Combined Parameter Check 35
6.3 New Check: Problem Flanks Check 36
6.4 Modified Check: Time gradient Check 37
6.5 Verification Results 38
6.5.1 Case Study 1: False Alarm of the QCSv3 Ext. Reference Check . . 39
6.5.2 Case Study 2: False Alarm of the QCSv3 Interstational Check . . 40
6.5.3 Case Study 3: Improved Detection of Problem Behavior 41

6.5.4 Case Study 4: Improved Detection of Truncated Values 41
6.5.5 Case Study 5: Improved Detection of Problem Behavior 41
6.5.6 Case Study 6: False Alarms in Old and New Versions 45
6.5.7 Comparison of the Fraction of Flagged Data 45

7 Summary and Conclusions **48**

List of Figures **50**

List of Tables **53**

References **54**

1 Introduction

Data from meteorological station networks is required by a number of scientific applications, ranging from the evaluation of climate and weather forecast models (see e.g. Prein et al. 2013; Kann et al. 2011) to research on meteorological processes (Pedersen et al. 2010). Especially data with high temporal and spatial resolution is needed because data from other sources such as satellites or weather radars is often not accurate enough. The WegenerNet station network was established in 2007 in order to provide such data (Kirchengast et al. 2014).

For the suitability of the data for scientific purposes, quality control of the data is crucial. The quality of WegenerNet data is ensured by the automatized Quality Control System (QCS), which is regularly being evaluated and improved. The quality of precipitation data with focus on the homogenity of different rain gauge models was analyzed by Szeberenyi (2014). The QCS algorithms related to precipitation were evaluated and improved by Scheidl (2014). Currently the homogenity of air temperature and relative humidity data is being analyzed by Ebner (2017).

This work intends to improve the quality of relative humidity data. The humidity sensors frequently showed malfunctions producing underestimations, which were not adequately addressed by the current QCS. Until now, the detection of this kind of malfunctions was largely dependend on manual inspection. The start of the malfunction had to be manually identified and all data measured at this sensor afterwards was basically distrusted.

The objective of this work is to analyse the observed malfunctions and to improve the QCS algorithms so that underestimations of humidity are identified in an automatized, objective, accurate and reliable way.

The improvements follow two main approaches: First, the relative humidity can be quite variable between neighboring stations, but a combined parameter, comprising relative humidity and air temperature, is more homogenous, and therefore allows a better interstational comparison. The second approach aims to detect the specific temporal behavior of a typical malfunction.

In Chapter 2, a basic overview of the WegenerNet and its quality control procedures is given. The focus hereby is on the quality control of relative humidity data.

The typical problem behavior of relative humidity sensors is analyzed in Chapter 3. First a problem description and the history of the problem are given. Then the typical behavior is presented in two case studies. Finally, the behavior of several alternative humidity parameters, like specific humidity or mixing ratio, during relative humidity problem behavior is analyzed.

In Chapter 4, a criterion to identify problem behavior, based on the comparison of humidity and temperature to neighboring stations, is introduced and justified.

This criterion is then extended into an algorithm that identifies sensors showing problem behavior on a daily basis, which is presented and verified in Chapter 5.

The improvements of the QCS are presented in Chapter 6. They comprise an implementation of the criterion, a quality check based on the specific temporal evolution of problem behavior, and an evaluation of the existing time gradient check. The improvements are verified by case studies and a statistical analysis.

Finally, the conclusion chapter gives a brief summary of the results and discusses possible further improvements.

2 The WegenerNet and its Quality Control System

In this chapter, a basic overview of the WegenerNet and its quality control procedures is given. Also the concept of neighbouring stations will be presented. The focus lies on the measurement and quality control of relative humidity data. General introductions to the WegenerNet are given in Kirchengast et al. (2014) and Kabas (2012). More extensive information about the Quality Control System is also given in Scheidl (2014).

2.1 The WegenerNet Climate Station Network

The WegenerNet is a network of climate stations in the south-east of Austria. It was established by the Wegener Center for Climate and Global Change in 2006. Its 166 stations are grouped in the two regions Feldbach and Johnsbachtal.

As per December 2017, the WegenerNet Feldbach Region contains 154 climate stations. It covers an area of about 23 $\times$ 18 km, with the stations being arranged approximately on a grid with a grid spacing of about 1.4 km (see Figure 2.1). Within the WegenerNet Feldbach Region area there are also two weather stations of the Austrian Central Institution for Meteorology und Geodynamics (ZAMG), located in the towns of Bad Gleichenberg and Feldbach. Data from these stations are used in the quality control of WegenerNet data for external comparison. However, they are not included in the WegenerNet data products.

There are different types of stations, each measuring a set of parameters including for example air temperature, relative humidity, liquid and solid precipitation, wind and peak gust, several soil parameters, air pressure, and net radiation. At most stations, the air temperature, relative humidity and liquid precipitation are measured. The temporal resolution of the measurements is five minutes, except for some soil parameters which have a resolution of 30 minutes. According to the topographic location of a station, it is assigned into one of five location classes (see Table 2.1).

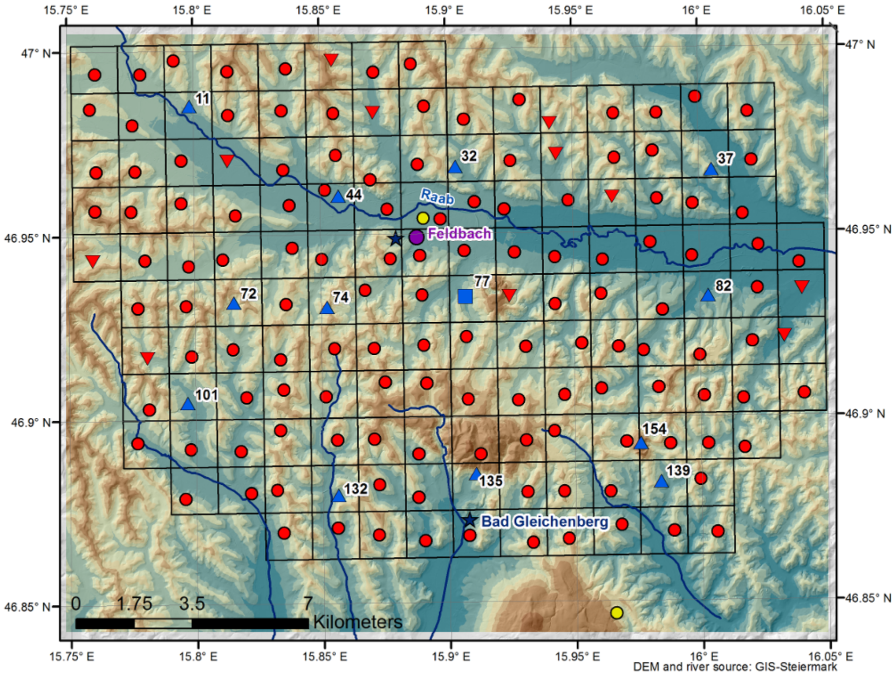


Figure 2.1: Spatial arrangement of the WegenerNet stations.

After being measured, the data are processed by the WegenerNet Processing System (WPS). First the data are transferred to the Wegener Center servers via GPRS, where they are stored in a database as Level 0 data (L0 data). These L0 data are then processed by the Quality Control System (QCS), where they run through a variety of automated checks and tests. The quality controlled data and the check results are stored as Level 1 data (L1 data). Finally the Data Product Generator (DPG) interpolates spatial and temporal gaps and generates grid data, data products with different temporal resolutions and added value data products, e.g. heat index maps, which are stored as Level 2 data (L2 data). WegenerNet data can be accessed online via the WegenerNet data portal (www.wegenernet.org).

The processing of WegenerNet data is designed to be near-realtime, i.e. the whole chain from measurement to online accessibility of quality controlled L2 data is run through within less than one and a half hours.

Table 2.1: Location classes of WegenerNet stations.

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

2.2 The Quality Control System of the WegenerNet

The QCS consists of several automated checks which are organized into eight layers (QC-layers). Each QC-layer can consist of several checks. An overview of the checks including a short description with focus on relative humidity data is given below. The results of the checks are expressed by a Quality Flag (QF). If a data value fails a check of QC-layer n, the value of 2^n is added to the QF. Only data values with a QF of 0, i.e. values that did not fail any checks, are used in the DPG. If a check could not be done, e.g. due to missing reference data, a *no_ref flag* is given. No_ref flagged precipitation data are not used in the DPG.

The analyses and improvements implemented within this work mainly relate to QC-layer 6, small changes are also done in QC-layer 4 and QC-layer 7.

QC-layer 0 – Operations check: Pseudo-check to allow manual flagging of data (e.g. during maintenance times). Data values flagged in this layer are set to "-9999" and skip all other layers.

QC-layer 1 – Availability check: In this layer it is checked whether the data for the tested time interval are available in the database. Missing database entries are created with a data value of "-9999" and a QC-layer 1 QF is set.

QC-layer 2 – Sensor check: In this layer it is checked whether a data value is within the technical min/max-specifications of the respective sensor. For relative humidity this values were specified by the manufacturer as 1 %rH and 104 %rH, respectively.

QC-layer 3 – Climatological check: In this layer it is checked whether a data value is within a reasonable climatological range. Monthly climatological minimum and maximum values were defined on the basis of long-time data of the ZAMG stations within the WegenerNet area. During the last years analyses of WegenerNet data led to some modifications of these values. For relative humidity the currently allowed range is 10 %rH to 104 %rH for all months.

QC-layer 4 – Time variability check: In this layer it is checked whether the 5-minute gradients are within a reasonable range. The allowed range was derived analogously to QC-layer 3. For relative humidity the allowed gradient range is −30 %rH to 30 %rH for all months. In this layer data are also checked for implausible constancy. The standard deviation of the last hour (the last three hours for air pressure and relative humidity >80 %rH) has to be larger than a threshold value. For relative humidity this value is 0.02 %rH.

QC-layer 5 – Intrastational check: In this layer the consistency of several parameters measured at the same station is checked. Relative humidity data are not checked in this layer.

QC-layer 6 – Interstational check: In this layer the measurements are compared to measurements of neighboring stations. Currently the interstational check of relative humidity data checks whether a data value is within a range of 20 %rH from the median of the neighboring station data values.

Neighborhood of two stations is defined upon topographic criteria. Depending on the distance, the location class and the difference in altitude, different levels of neighborhood are possible (see Table 2.2).

Table 2.2: Neighborhood levels for relative humidity

Neigborhood Level	Distance	Altitude difference	Location class
1	< 2.5 km	< 75 m	same
2	< 5 km	< 75 m	same
3	< 2.5 km	< 75 m	adjacent
4	< 5 km	< 75 m	adjacent

The QCS tries to use neighbors of a level as low as possible. Starting with level one, the stations of the next higher neighborhood level are added successively until a minimum number of neighbors is reached. If all levels are considered and the minimum number is still not reached, a no_ref flag is set. For relative humidity the minimum required number of neighbor stations is five.

QC-layer 7 – External reference check: In this layer relative humidity and air pressure data are compared to the measurements of the ZAMG stations within the WegenerNet.

3 Characterization of Relative Humidity Problem Sensor Behavior

In this chapter the characteristics of relative humidity problem behavior are analyzed. First the basic problem and how it was dealt with in the past is discussed. Then the typical behavior is presented in two case studies. Finally, the behavior of several alternative humidity parameters, like specific humidity or mixing ratio, during problem behavior is analyzed.

3.1 Relative Humidity Problem Behavior

It is a known problem that from the very beginning of the WegenerNet certain relative humidity sensors tended to underestimate relative humidity, especially for high values. The reason of this underestimation is probably mainly due to degradation caused by contamination. If the underestimation was drastic enough, it was detected by the QCS, especially by the comparison to ZAMG data in QC-layer 7. If the underestimation was too small, however, it was not detected by the QCS, while easily being recognized manually when looking at time series.

In a first attempt to handle this problem, the *problem mode* concept was introduced: Sensors showing suspicious behavior could be manually assigned problem mode flags for distinct timespans, which were stored in the database. Values from sensors in problem mode were specially labelled in the web portal. During the last years, the concept of problem mode was expanded and each sensor was assigned a sensor status (see Table 3.1). However, there was neither a systematic analysis of the characteristic problem behavior, nor a standardized approach in the detection of problem sensors and in the assignment of the problem mode.

Between October 2014 and May 2016 the relative humidity sensors have been replaced in several tranches.

Table 3.1: List of sensor statuses

Status	Description
1	ok
2	problem mode
3	unknown
4	out of operation

3.2 Case Studies of Sensors Showing Problem Behavior

3.2.1 Case Study – Station 20: Evolving Problem Behavior

In this case study the slow evolution from normal to problem behavior of the sensor installed at station 20 is analyzed (see Figure 3.1). In April 2009 the sensor still measured correctly. Most of the time it measured even higher values than its neighbors. Then starting in June, the sensor started to underestimate values higher than about 87 %rH. In October 2009 the sensor is obviously malfunctioning. The timeline shows inverse behavior for values higher than about 75 %rH. The QCS produces some false alarms in April. While the truncation in July is not detected by the QCS, the obviously bad values in October are basically detected. However, the beginning and ending of underestimations are often not captured accurately.

This case study is a good example for the typical evolvement of sensors from normal to problem behavior. There is a threshold above which values are underestimated and the threshold slowly drops over time. If the real relative humidity is slightly above this threshold, the values are truncated. If the real humidity is much higher than the threshold, the measured time series show inverted behavior. This kind of problem behavior is probably due to the slow degration of the sensor by contamination. Also the performance of the QCS is typical: While seriously bad values are detected quite good, the detection of truncations and transitions from correct to incorrect values (and vice versa) could be improved.

3.2.2 Case Study – Station 87: Sudden Problem Occurrence and Recovery

In this case study the sudden occurence of problem behavior and slow recovery to normal operation of the sensor installed at station 87 is shown. As depicted in Figure 3.2, the sensor showed perfectly correct behavior until, on October 23, 2009, the measured value suddenly dropped to about 40 %rH, appearently due to sensor contamination. The threshold above which underestimation occurs appearently dropped to about 75 %rH and increased again during the following weeks. By November it was about 85 %rH and in December the sensor recovered well enough to measure values as high as 95 %rH.

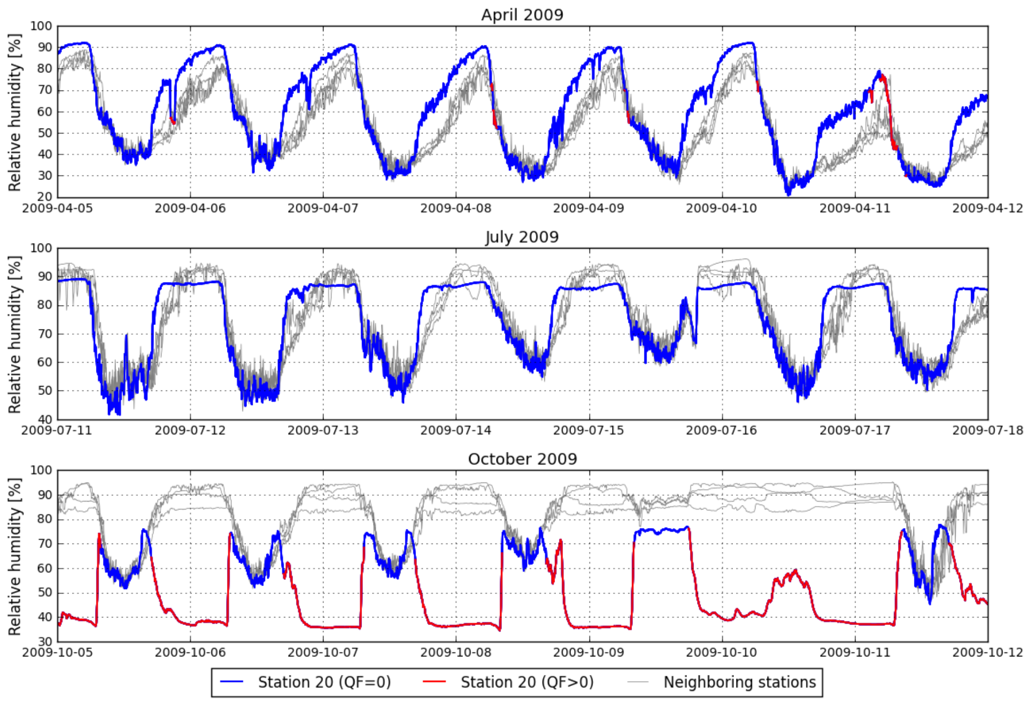


Figure 3.1: Relative humidity at station 20 (blue) and selected neighbor stations (grey) for April, July and October 2009. Quality flagged relative humidity values at station 20 are indicated by the red color.

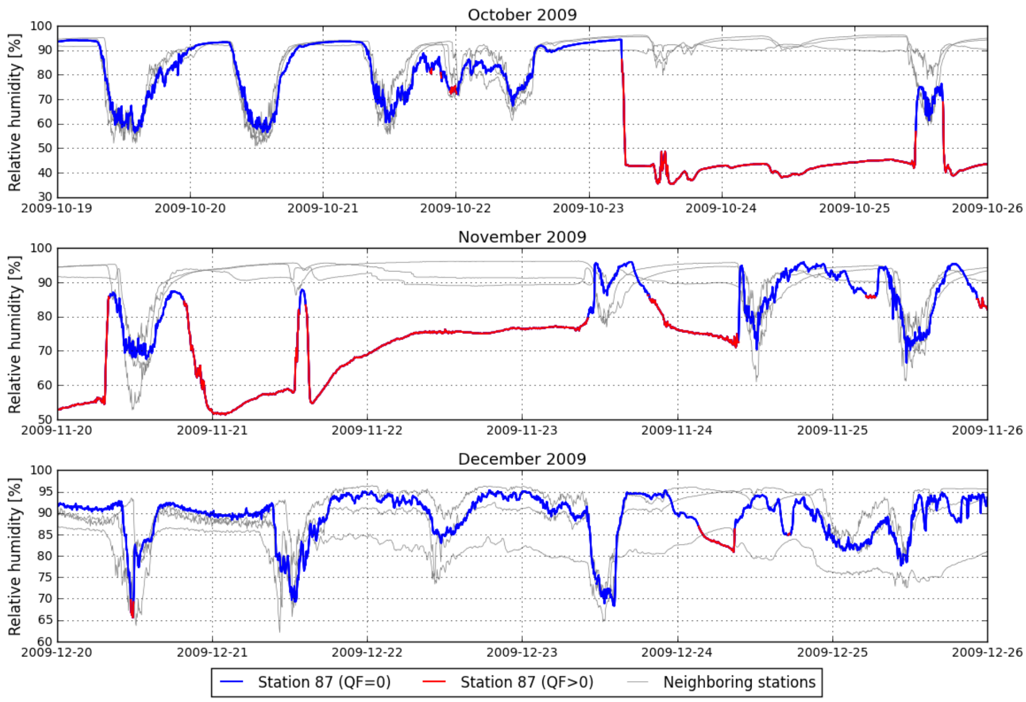


Figure 3.2: Relative humidity at station 87 (blue) and selected neighbor stations (grey) for October, November and December 2009. Quality flagged relative humidity values at station 87 are indicated by the red color.

3.3 Analysis of Different Humidity Parameters during Problem Behavior

In a first approach to improve the detection of problematic relative humidity values, the behavior of other humidity parameters during times of problem behavior was analyzed. Relative humidity (RH [%]), water vapor pressure (e [hPa]), absolute humidity (AH [g/m^3]), specific humidity (q [g/kg]), and mixing ratio (r [g/kg]) of a problem station and its neighbor stations were plotted for several case studies. Additionally the air temperature (T [°C]), the air pressure (p [hPa]), and the saturation vapor pressure (e_s [hPa]) were plotted. Since air pressure is not measured at every station, data from station 77 (reference station) were used.

The saturation vapor pressure was calculated using the formula given by Jarraud (2008):

$$e_s = 6.112 * \exp\left(\frac{17.62 * T}{243.12 + T}\right) * \left(1.0016 + 3.15 * p * 10^{-6} - \frac{0.074}{p}\right)$$

The other parameters were defined as follows (Kraus 2007):

$$\begin{aligned} e &= RH * es * 10^{-2} \\ AH &= \frac{e}{462 * (T + 273.15)} * 10^5 \\ q &= \frac{0.622 * e}{p - 0.378 * e} * 10^3 \\ r &= \frac{0.622 * e}{p - e} * 10^3 \end{aligned}$$

The case studies included clear summer nights with inversions, days with precipitation, and foggy winter days. In Figure 3.3 the case study of station 20 during a summer night inversion in August 2009 is shown. The characteristic underestimation of humidity is obvious for all humidity parameters. However, none of them shows a behaviour substantially different from relative humidity. This behavior was found in all case studies and therefore it was concluded that an approach based on these humidity parameters is not expedient. Another approach based on a combination of relative humidity and air temperature is presented in Chapter 4.

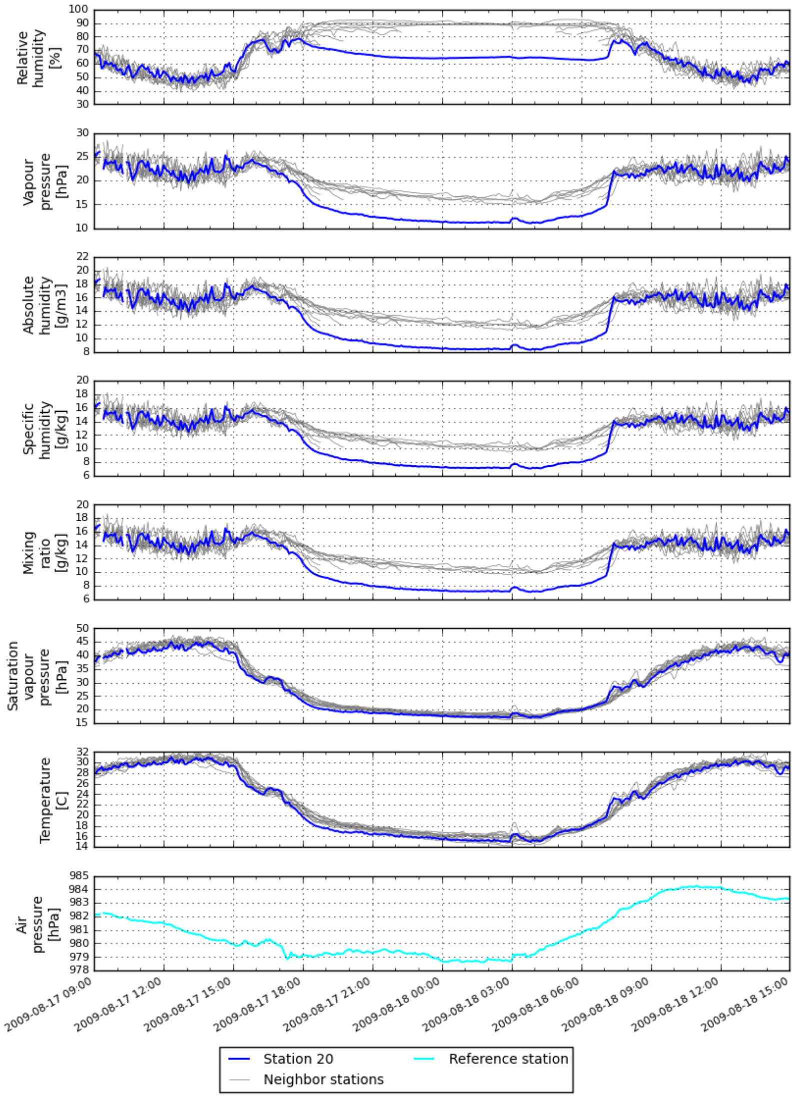


Figure 3.3: Different humidity parameters, saturation vapor pressure, and air temperature at station 20 (blue) and its neighboring stations (grey) and air pressure at station 77 (light blue) from August 17, 2009 09:00 UTC to August 19, 2009 15:00 UTC. Only neighbor data unflagged by the QCS are plotted.

4 Definition of a Criterion for Problematic Humidity Values

In this chapter a criterion to automatically identify problem sensors is presented. In the first section the list of neighborhood levels for relative humidity is extended. In section two the criterion is presented. In the third section the derivation of the criterion is presented and justified with some case studies.

4.1 Extended Neighborhood Levels

As mentioned above, there where times when the fraction of malfunctioning humidity sensors was rather high. Consequently the interstational quality checks were obstructed because very few neighbor stations provided correct humidity reference data. Sometimes less than two correct neighbors were available, even when considering all neighborhood levels. In order to make interstational checks possible nonetheless, the list of neighborhood levels for relative humidity was extended with four new levels allowing distances up to 20 km. The updated list of relative humidity neighbor levels is given in Table 4.1.

Table 4.1: Extended neighborhood levels for relative humidity

Neigborhood Level	Distance	Altitude difference	Location class
1	< 2.5 km	< 75 m	same
2	< 5 km	< 75 m	same
3	< 2.5 km	< 75 m	adjacent
4	< 5 km	< 75 m	adjacent
5	< 10 km	< 75 m	same
6	< 10 km	< 75 m	adjacent
7	< 10 km	any	any
8	< 20 km	< 250 m	adjacent

4.2 Definition of the Problem Behavior Criterion

The approach was to find a criterion for problematic humidity values that is based on an interstational comparison and – in contrast to the existing QCS checks – takes into account not only the relative humidity measurements, but also the corresponding measurements of air temperature.

The criterion is defined for data with a resolution of five minutes that were smoothed by applying an unweighted running mean filter with a window of 13 measurements (65 minutes).

In order to check a relative humidity candidate value RH_{cand} (with a corresponding air temperature value T_{cand})), a relative humidity reference value (RH_{ref}) and a temperature reference value (T_{ref}) are determined. As potential reference stations, the relative humidity neighbor stations as defined in Table 4.1 are considered. Stations with sensors in problem mode are excluded. If there are at least 10 remaining stations in neighborhood level 1, they are used as reference stations. Else the stations of the next neighborhood levels are added successively until there are at least 10 reference stations or all levels have been added.

If the number of reference stations is uneven, RH_{ref} is the median of the relative humidity values of the reference stations. Otherwise RH_{ref} is the upper of the two middle values (i.e. the next higher value to the median). T_{ref} is the air temperature value of the station that measured RH_{ref}. If more than one reference station measured RH_{ref} the choice between them is random.

The criterion for problem behavior is defined as:

$$\Delta RH\,[\%] < -4 * \Delta T\,[°\text{C}] - 10$$

with

$$\Delta RH = RH_{cand} - RH_{ref}$$

$$\Delta T = T_{cand} - T_{ref}$$

The criterion is valid within the temperature-difference range $|\Delta T| \leq 4\,°\text{C}$.

4.3 Derivation of the Problem Behavior Criterion

The criterion was set up using scatterplots of ΔRH against ΔT, hereafter called *diagnose plots*. Such diagnose plots were produced for a number of assumedly good sensors and obvious problem sensors. The sensors assumed to be good were newly replaced sensors. Additionally the data of these sensors were manually controlled.

It turned out that the scatterpoints show a rather linear behavior within a confined space for good sensors. For problematic data values, on the other hand, the scatterpoints leave this confined space. The criterion is a manually fitted threshold line that is trespassed only by an insignificant fraction of the scatterpoints from assumedly good sensors.

Physically, an allowed range would be more appropriate than a threshold line and would in principle allow to check for overestimations too. However, significant overestimations of relative humidity are not expected and false alarms due to underestimating neighbors seem likely. Also the focus in this work was on detecting underestimations. Therefore a simple threshold line was chosen.

In the following subsections a number of diagnose plots is presented.

4.3.1 Comparison of Good and Problem Sensor Diagnose Plots

In this subsection three case studies, showing different weather events, are presented. For each case study, the diagnose plots of an assumedly good sensor and an apparent problem sensor are contrasted. Additionally, time series of the candidate relative humidity data before and after smoothing, and the smoothed data of the reference stations are given for both sensors. Data points fullfilling the criterion for problem behavior are distinctly marked in the time series.

The details of the case studies are given in Table 4.2. The analyzed timespan ranges from 09:00 UTC on the given date until 15:00 UTC on the following day.

Table 4.2: Case studies for different weather conditions

Case study	**Date**	**Weather**	**Station Nr.**		**Shown in**
			Good	Problem	
1	August 19, 2015	Rainfall	37	108	Figure 4.1
2	December 19, 2014	Inversion	27	3	Figure 4.2
3	August 07, 2015	Inversion	34	65	Figure 4.3

None of the data from the assumedly good sensors fullfilled the criterion. For the problem sensors the criterion was fullfilled by 40% of the data points in Case study 1, 34% in Case study 2, and 21% in Case study 3.

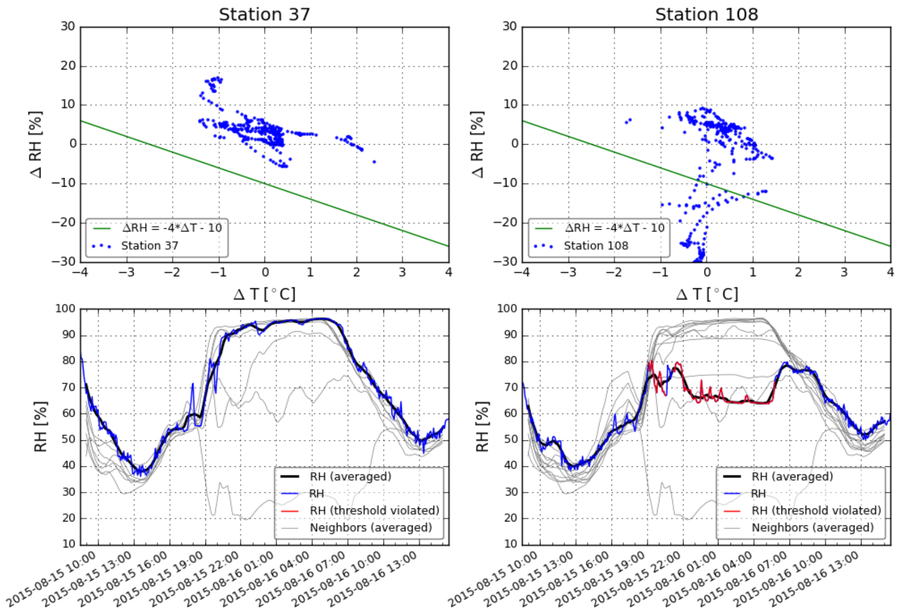


Figure 4.1: Diagnose plots (upper row) and time series (lower row) for an assumed good sensor (station 37, left column) and a known problem sensor (station 108, right column) from August 15, 2015 09:00 UTC to August 16, 2015 15:00 UTC. The diagnose plots show ΔRH against ΔT (blue) and the criterion threshold (green). The time series show the relative humidity data of the station (red if violating the threshold, otherwise blue), the time-averaged relative humidity data of the station (black) and its reference stations (grey).

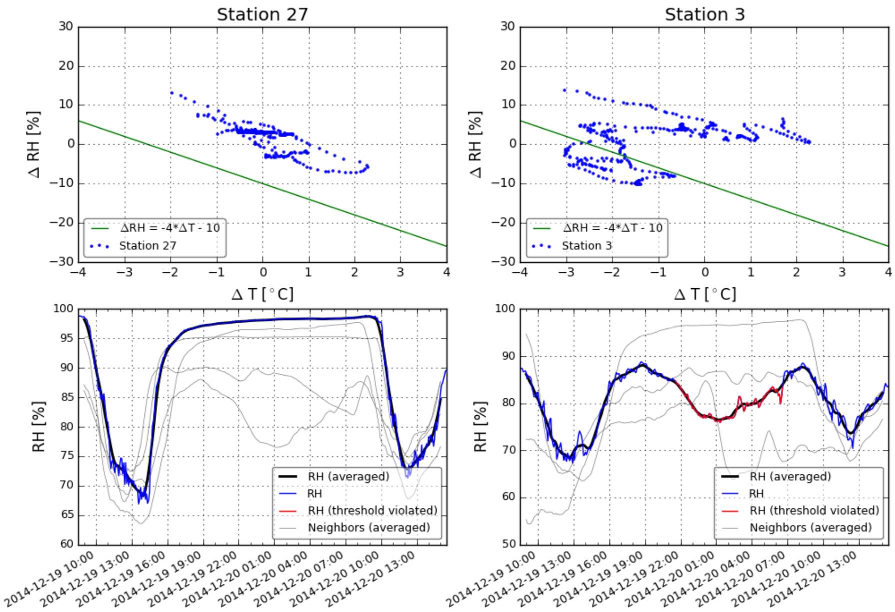


Figure 4.2: Diagnose plots (upper row) and time series (lower row) for an assumed good sensor (station 27, left column) and a known problem sensor (station 3, right column) from December 19, 2015 09:00 UTC to December 20, 2015 15:00 UTC. The diagnose plots show ΔRH against ΔT (blue) and the criterion threshold (green). The time series show the relative humidity data of the station (red if violating the threshold, otherwise blue), the time-averaged relative humidity data of the station (black) and its reference stations (grey).

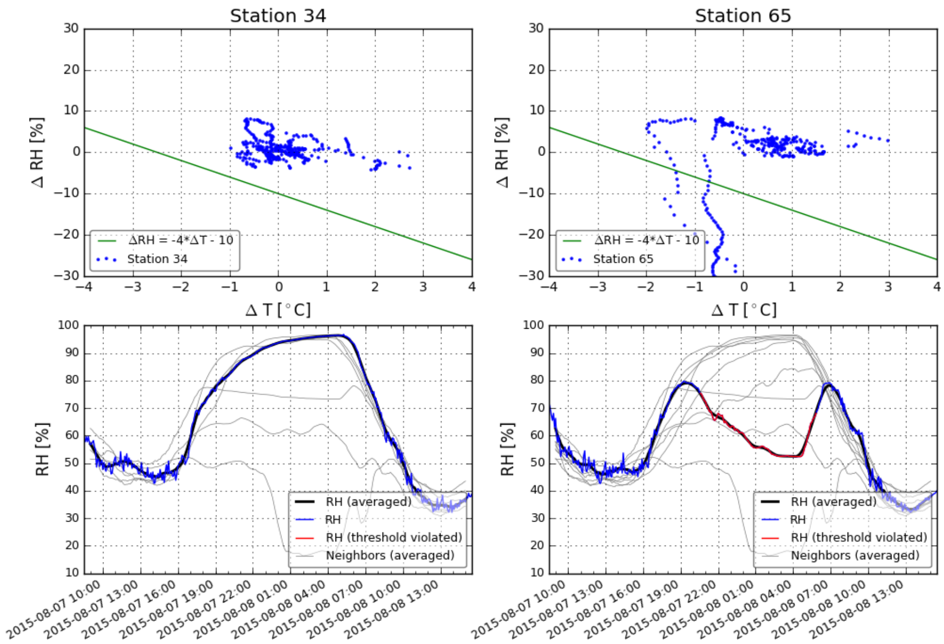


Figure 4.3: Diagnose plots (upper row) and time series (lower row) for an assumed good sensor (station 34, left column) and a known problem sensor (station 65, right column) from August 07, 2015 09:00 UTC to August 08, 2015 15:00 UTC. The diagnose plots show ΔRH against ΔT (blue) and the criterion threshold (green). The time series show the relative humidity data of the station (red if violating the threshold, otherwise blue), the time-averaged relative humidity data of the station (black) and its reference stations (grey).

4.3.2 Dependence on Location Class and Season

In order to verify the validity of the criterion for different location classes and seasons, further diagnose plots were produced. They include the data of 24 assumedly good sensors within one month. Different location classes are distinctly marked. For each of the location classes valley, middle slope, and ridge, eight sensors were selected. They are given in Table 4.3.

Table 4.3: Station numbers of selected, assumedly good sensors according to location class.

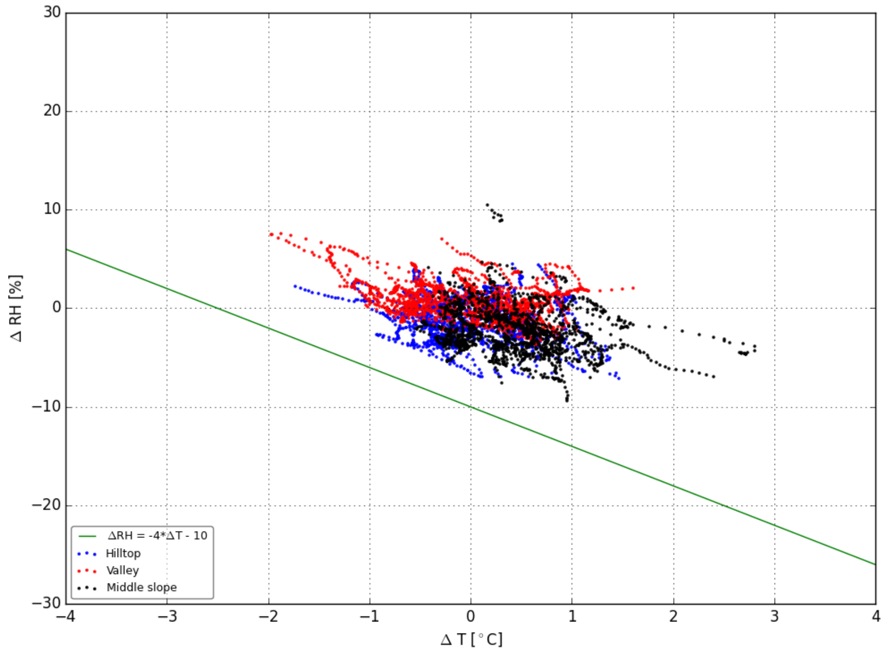
Location class	**Station numbers**
Valley	27, 44, 57, 66, 72, 84, 99, 101
Middle slope	14, 34, 54, 77, 78, 82, 125, 135
Ridge	4, 6, 25, 37, 70, 74, 114, 150

In Figure 4.4 the plots for January 2015 and July 2015 are shown. In January 2015 none of the data fullfilled the criterion. In July 2015 0.17% of the data from the location class ridge, 0.13% of the location class valley, and none of the location class middle slope fullfilled the criterion.

Comparing the two plots, it seems that the distribution of scatterpoints is dependent on the season. Appearently the relative humidity field is more variable in summer.

Also, there is a bias related to the location class. It seems that most of the time the relative humidity is higher on the valley floor than on the ridge. If neighbors from lower location classes are used as references, the relative humidity reference value is biased towards higher values. Therefore hilltop stations are more prone to false alarms.

However, the criterion has enough tolerance to keep the number of false alarms acceptable.



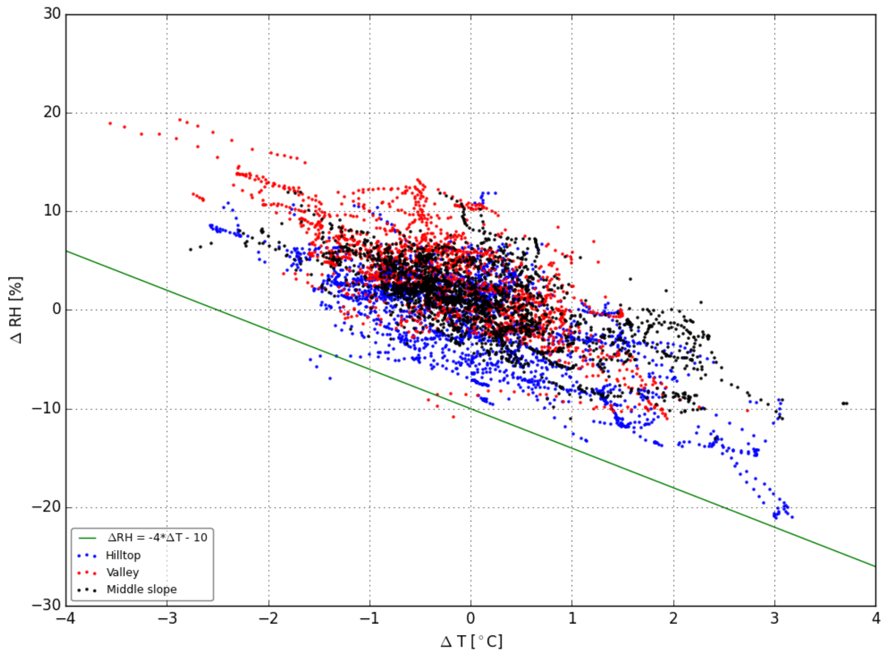


Figure 4.4: Diagnose plots for January 2015 (upper) and July 2015 (lower) according to the location classes valley (red), middle slope (black) and ridge (blue). The criterion threshold is plotted in green.

5 Automatic Problem Sensor Status Identification

As described in Section 3.1, the assignment of sensor statuses is currently done manually. In this chapter, a Python script is presented, which will automatize the assignment of sensor statuses based on the criterion for problematic humidity values (see Section 4.2). In the first section the implementation of the script into existing (re-)processing routines is explained. In the following section the algorithm is described and the script options are given. Finally the results of processing the WegenerNet data from 2007 to 2016 with the script are presented.

5.1 Implementation into (Re-)Processing Routines

In routine processing the script is run daily at 00:15, evaluating the data of the day before yesterday. The runtime of the script is about 20 seconds.

The script was implemented into routine processing on January, 25 2017. All data dating from before that was reprocessed in one run.

The results of the script (i.e. the sensor status assignments) are written to the database table containing the sensor statuses, in which also the manual status assignments are stored. In order not to overwrite them and thereby loose information, manual entries overrule automatized check results on their first day. More details on the database entry procedure are given in the corresponding paragraph of the following section.

5.2 Algorithm Description

When running the script a number of options can be specified. They are given in Table 5.1. The script processes single days. If the timespan to be processed is longer than one day, the script is applied consecutively to every day.

The algorithm can be broken down to four parts: data preparation, reference values selection, actual check and database entry.

Table 5.1: Script options

Option	Description	Default
`--start START`	Start of the interval to be processed. START is in format 'YYYY-MM-DD'.	Yesterday
`--end END`	End of the interval to be processed. END is in format 'YYYY-MM-DD'. (The processed period must be at least one day.)	Today
`--stations STAT`	Station numbers of the sensors to be checked. STAT is a comma separated integer range (e.g. 1, 20-24, 86).	1-154
`--use-l1-version VE`	Level 1 data version to be used. VE is an integer.	3
`--dry`	Results are not written to the database.	False
`--monitor`	Shows a plot monitoring the status of all sensors during the last month before --end.	False
`--load-counter`	Tries to load counter values from an external file. *To be used in routine processing!*	False
`--reprocess-status4`	Reprocess sensors with status 'out of operation'. *This may lead to inconsistencies!**	False

* Example: A sensor was manually set to status 'out of operation' and removed some time after. If this option is active, the script will believe the manual assignment for one day, but the end date of the manual assignment, i.e. the date when the sensor was removed, will be lost. Therefore the last automatized status assignment may remain active even after the sensor was removed.

Data preparation: First, all obviously bad data are excluded. Data are assumed to be obviously bad, if they fail the following conditions:

$$-50\,^{\circ}\mathrm{C} < T < 50\,^{\circ}\mathrm{C}$$

$$0\,\% < RH < 100\,\%$$

The data are then smoothed by applying an unweighted running mean filter with a window of 13 measurements (65 minutes). If possible the window is centered at the candidate value. If this is not possible because data are not available (yet), e.g. in near-realtime processing of the QCS, the window shifts into the past.

Reference values selection: Basically, the reference values are determined like described in Section 4.2. As shown above, data from sensors that are already in problem mode are not considered as references. A problem sensor is defined as a sensor being in problem mode at 00:00 UTC of the processed day. This implies that if a station is set to problem mode manually with a begin date other than 00:00 UTC, this is ignored for the first day. There is no minimum number of neighbors required.

Actual check: The criterion given in Section 4.2 is applied to every 5 minute timestep of the processed day. If more than 20% of the 5-min timesteps have invalid data (i.e. either the temperature or relative humidity values are obviously bad or missing), the check is invalid. If the criterion is fullfilled by more than 20% of the 5-min timesteps of the day, the sensor is considered a problem sensor.

Database entry: First the current sensor status is queried from the database. In case one entry ends and another begins during the processed day, the ending entry is used as the current entry.

If the current status and the check result agree on the status (i.e. either both OK or both problem sensor), obviously no database entry is made. Also if the check is invalid, no database entries are made.

If the current status and the check result disagree, the current entry is ended as of 23:59:59 UTC of the day before and a new entry with a status according to the check, starting at 00:00:00 UTC and ending at the end date of the current status is created.

There are three exceptions to the normal database entry process:

1. If there exists a manual database entry for the processed day, no entry is made until midnight of this day. This is done in order not to overwrite manual entries.

2. If the current status is "out of operation", no entry is made regardless of the check results. This rule can be surpressed by setting the script option `--reprocess_status4`.

3. If the sensor status was "problem_mode" for more than seven consecutive days, the sensor enters *permanent problem mode*. This means it is only allowed to change to status "OK" again if the check is passed positively for more than 14 consecutive days.

   In daily routine processing the test results of the last 14 days are not automatically available. Therefore the 14 days-count can be saved to and retrieved from an external counter file (script option --load-counter).

5.3 Verification Results

The script was tested on a number of case studies. One of them is presented in Figure 5.1. It shows the sudden start of problematic behavior at station 19. The automatic problem sensor identification correctly identified the problem behavior starting on October 21, 2010 and changed the sensor status from OK to problem mode .

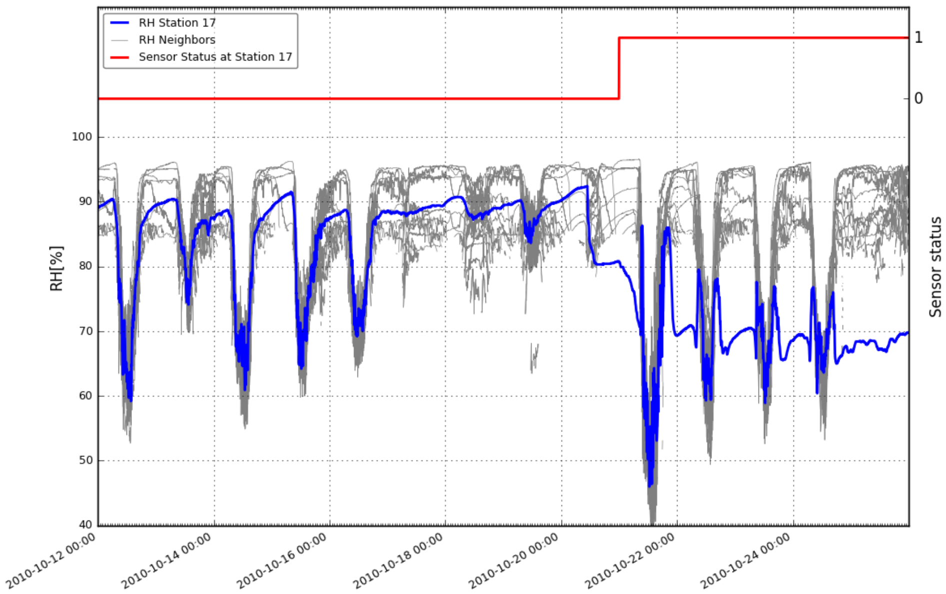


Figure 5.1: Relative humidity at station 19 (blue), measurements of neighboring stations (grey), and assigned sensor status (red; 0: OK, 1: Problem mode) at station 17 from October 12, 2010 to October 25, 2010.

After testing the script, the WegenerNet data from 2007 to 2016 were processed. The resulting automatized status assignments were then compared to the original manual status assignments in two different plots.

In Figure 5.2, the timeline of the number of sensors in each status is given for both automatized and manual assignment. Besides giving a general overview of the temporal development of the sensor quality, this plot reveals that:

- The timelines of both status assignment procedures are consistent in that they follow the same general trends.
- The timeline from automatized status assignment shows a pronounced annual cycle, with more sensors in problem mode in winter than in summer. This seems reasonable since problematic behavior is more likely to occur during the generally more humid winter months.
- Most of the time the number of sensors in status “OK” is higher from automatized status assignment than from manual assignment. This can be contributed to the fact that the automatic assignment allows sensors to change back to status “OK” after an episode of problematic behavior, while with manual assignment, problem mode sensors were not reinspected on a regular basis.

In another plot, the timelines of statuses from both automatized and manual assignment are shown individually for each sensor. In Figure 5.3 this kind of plot is illustrated for some selected sensors. These kind of plots served as a source of case studies which further backed the above mentioned observation that the easier switching back to status “OK” increases the number of available “OK” sensors. In Figure 5.3 this is exemplified by the sensors 31, 47, 78 and 91. Another finding was that the automatized status assignment identified problematic behavior earlier than manual assignment (e.g. sensors 84, 98) and even found problemetic behavior totally undetected by manual inspection (e.g. sensor 17).

Summing it up, the automatic sensor status assignment seems to improve the accuracy of sensor statuses. On the one hand, problematic behavior is detected earlier and more reliable. On the other hand, the number of unjustified problem mode assignments is diminished by easier switching between the sensor statuses.

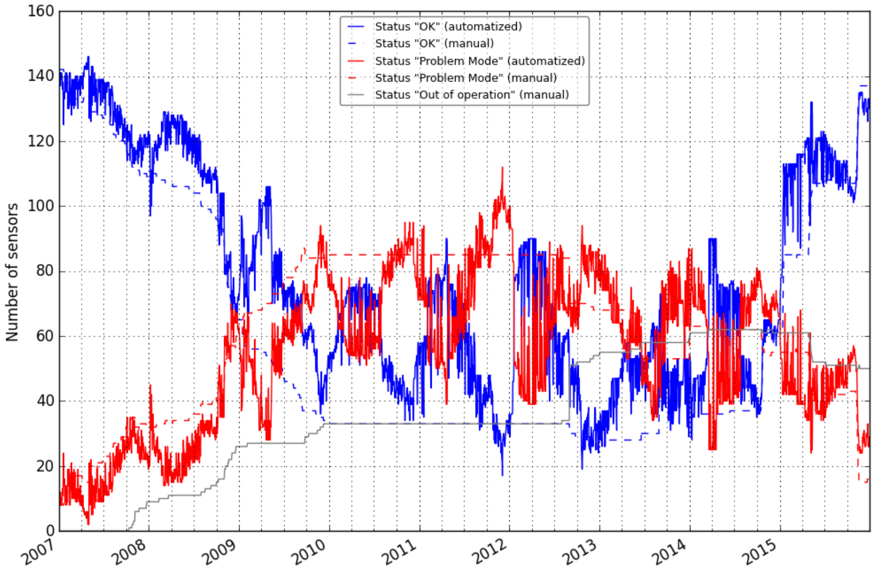


Figure 5.2: Temporal development of the number of sensors in status "OK" (blue), "problem mode" (red) and "out of operation" (grey) from 2007 to 2016. The manual and automatized assignments are given in dashed and solid line, respectively.

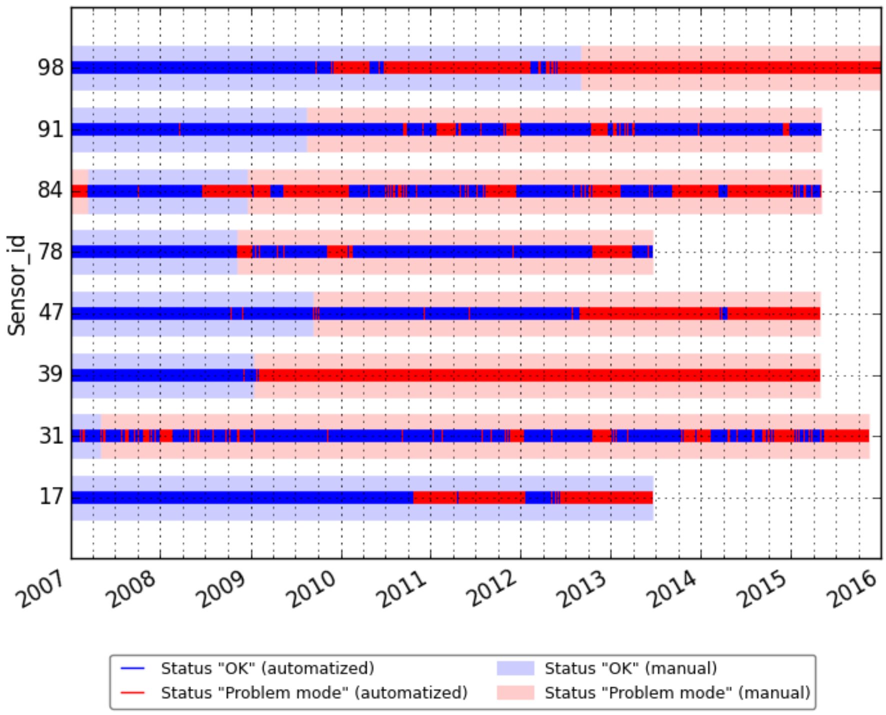


Figure 5.3: Temporal development of sensor status from automatized assignment (opaque) and manual assignment (transparent) for some selected sensors. The statuses “OK” and “problem mode” are indicated by blue and red color, respectively.

6 Improvements of the Quality Control System

Based on the results of the evaluation of the Quality Control System (QCS) in regard to relative humidity problem behavior (see Chapter 3) and the criterion for problem behavior (see Chapter 4), several modifications of the QCS were implemented.

In the first section the implementation of the modifications into the existing QCS is described.

Two new quality checks for relative humidity data were created, which are presented in the two following sections. One of them is a rather straight-forward implementation of the criterion for problem behavior. The other one focuses on transitions between correct and problematic values.

The fourth section gives the results and the consequences of an evaluation of the time gradient check of relative humidity data in QC-layer 4.

Finally, the validity of the changes is verified and the results of a reprocessing of the WegenerNet data are presented.

6.1 Implementation into (Re-)Processing Routines

The modified QCS is introduced to the WPS as QCS version 4 (QCSv4). The basic processing routine of the QCS is not changed. The QCS runs hourly for all new data and again daily, reprocessing the day before yesterday. Since the server infrastructure and database structure were improved in parallel to the modifications, the runtime of the QCS did not increase noticeably.

The old interstational check for relative humidity in QC-layer 6 is completely replaced by the two new checks presented below.

The external reference check, comparing relative humidity data to ZAMG data in QC-layer 7, is run only for data that got a no-ref flag in the newly introduced combined parameter check (i.e. if data from less than five neighbor stations were available). This was done because the external reference check produced quite many false alarms and is dispensable due to the new checks.

Also the extended neighborhood levels as given in Section 4.1 were implemented into the QCS.

6.2 New Check: Combined Parameter Check

The combined parameter check applies the criterion for problem behavior on a single relative humidity measurement RH_{cand}. The corresponding air temperature value is labeled as T_{cand}.

The relative humidity neighbor stations as defined in Table 4.1 are considered as potential reference stations. Stations with sensors in problem mode are excluded. For each potential reference station, the mean value of relative humidity RH_{neigh} and air temperature T_{neigh} within a time window of 65 minutes is calculated. Only data that has no quality flags in the QC-layers 0-2 is used. If possible the time window is centered at the candidate value. If this is not possible because data are not available (yet), e.g. in the hourly near-realtime processing, the window shifts into the past.

If RH_{neigh} and T_{neigh} could be calculated for at least five stations of neighborhood level 1, they are used. Else the stations of the next neighborhood levels are added successively until there are at least five reference stations or all levels have been added. If the neighbors of all neighborhood levels have been added and there are still less than five RH_{neigh} and T_{neigh} values available, a no_ref flag is set.

If the number of used reference stations is uneven, RH_{ref} is the median of the RH_{neigh} values. Otherwise RH_{ref} is the upper of the two middle values (i.e. the next higher value to the median). T_{ref} is the air temperature value of the station that measured RH_{ref}. If more than one reference station measured RH_{ref} the choice between them is random.

The actual check is then:

$$\Delta RH\,[\%] \leq -4 * \Delta T\,[°\mathrm{C}] - 10 \vee |\Delta T|\,[°\mathrm{C}] > 4$$

with

$$\Delta RH = RH_{cand} - RH_{ref}$$

$$\Delta T = T_{cand} - T_{ref}$$

If the check is failed, i.e. the above equation is true, a quality flag is set.

In principle the possibility to have distinct check parameters for sensors in problem mode is implemented, but for the time being the same check parameters are used regardless of the sensor status.

6.3 New Check: Problem Flanks Check

As discussed in Section 3.2, one of the weaknesses of the old QCS was the detection of problem behavior during transitions from correct to incorrect values. Since this weakness is not sufficiantly resolved by the combined parameter check, the problem flanks check was introduced.

The basic idea of this check is that a candidate sensor is flagged if it has a negative trend while its neighbors have an increasing trend. The flagging then continues until the discrepancy between the trends ends. In order to reduce the number of false alarms the check is only run for problem sensors and if the humidity is rather high (>80%).

In order to check a relative humidity value at a candidate station, the following check variables are needed:

- The problem flanks check result of the preceding value (5 minutes before) at the candidate station.
- S_C...The slope of a linear regression of candidate station values within a time window of 65 minutes. If possible, this time window is centered at the candidate value. If this is not possible because data are not available (yet), e.g., in near-realtime processing of the QCS, the window shifts into the past.
- S_N...The median of the slopes of at least five neighbor stations. The slopes of the neighbors are each calculated analogously to S_C. If the slopes could be calculated for at least five stations of neighborhood level 1, they are used. Else the stations of the next neighborhood levels are added successively until there are at least five slopes available or all levels have been added.
- M_N... The median of the mean relative humidity values of at least five neighbor stations within a time window of 65 minutes. The time window and the neighbor selection are handled as above.

If one of those check variables can not be determined, a no_ref flag is set. Otherwise there are two posibilities:

1. If the preceding value was not flagged in the problem flanks check and $M_N > 80\,\%\text{rH}$ and $S_N > 0\,\%\text{rH}/5\,\text{min}$ and $S_C < 0\,\%\text{rH}/5\,\text{min}$, the candidate value is flagged.
2. If the preceding value was flagged in the problem flanks check, the candidate value is flagged too, unless:
   - $M_N < 80\,\%\text{rH}$ or
   - $S_N < 0.1\,\%\text{rH}/5\,\text{min}$ and $S_C < 0.1\,\%\text{rH}/5\,\text{min}$ or
   - $S_N > 0.1\,\%\text{rH}/5\,\text{min}$ and $S_C > 0.1\,\%\text{rH}/5\,\text{min}$.

6.4 Modified Check: Time gradient Check

As part of reviewing the quality checks on relative humidity, also the time gradient check in QC-layer 4 was revised. The validity of the thresholds was analyzed in some case studies, two of which are presented here.

As a result of reviewing these case studies, the thresholds for the time gradient check were changed from ±15 %rH/5 min to ±30 %rH/5 min for all months.

The first case study shows a thunderstorm event from May 28, 2012 (see Figure 6.2). In this event the humidity increased dramatically and the threshold was exceeded at 22 stations within less than half an hour. Six sensors measured gradients of more than 20 %rH/5 min.

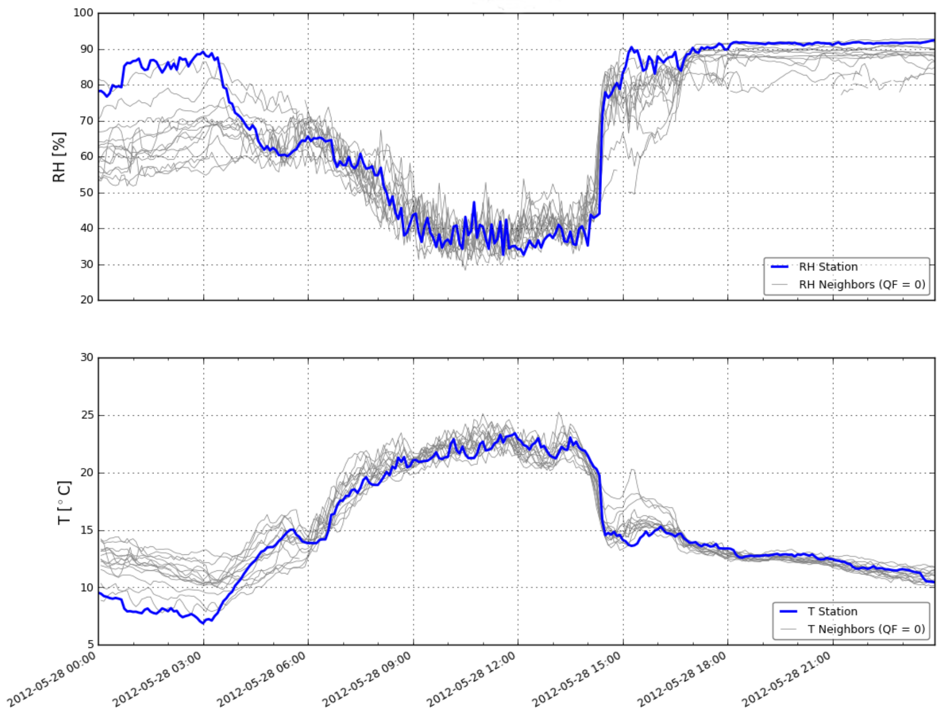


Figure 6.1: Relative humidity (upper plot) and air temperature (lower plot) at station 130 (blue) and unflagged measurements at neighboring stations from May 28, 2012 to May 29, 2012.

The second case study dates from March 25, 2008 and is shown in Figure 6.1. In this event the humidity was governed by fast drying dew and the replacement of the air mass by dry air with wind speeds of about 20 km/h. Between 07:45 UTC and 10:00 UTC the threshold was exceeded at 22 stations.

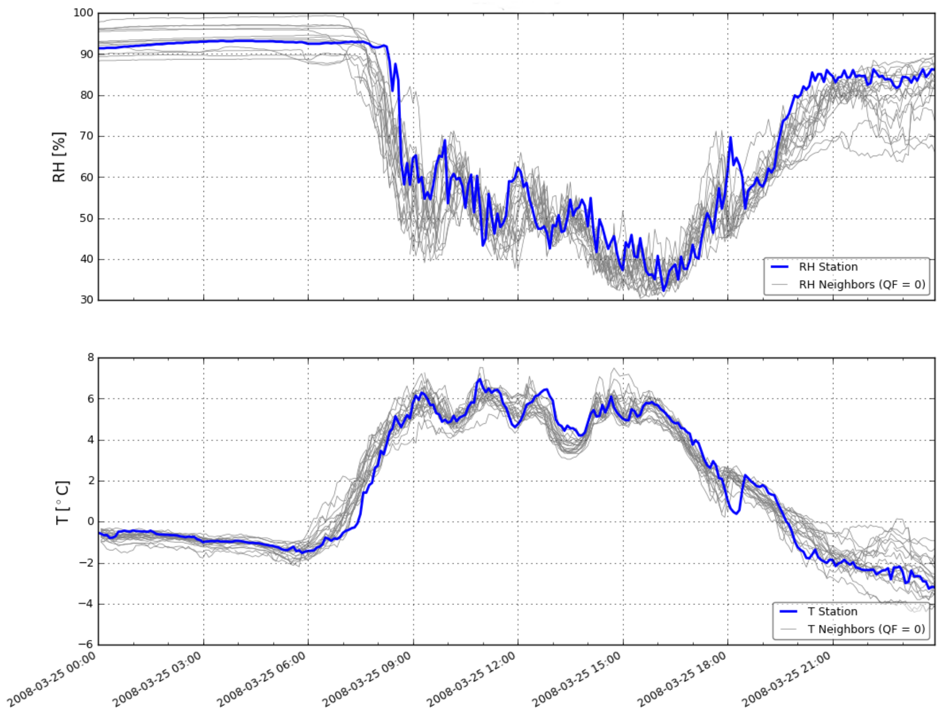


Figure 6.2: Relative humidity (upper plot) and air temperature (lower plot) at station 130 (blue) and unflagged measurements at neighboring stations from March 25, 2012 to March 26, 2012.

6.5 Verification Results

The modifications done to the QCS were tested on several case studies. Six of them are presented in this section. They focus on functional differences between the old version and the modified version. Case studies comparing different weather events were partly done, but did not reveal any fundamentally different results.

In the last subsection a statistical analysis of a reprocessing of several years is presented.

The old QCS version without the modifications is henceforth referred to as QCSv3, the modified version is referred to as QCSv4.

6.5.1 Case Study 1: False Alarm of the QCSv3 Ext. Reference Check

The first case study dates from March 29, 2014 06:00 UTC to March 30, 2014 18:00 UTC and is shown in Figure 6.3. Air temperature and humidity follow a diurnal cycle with quite constant gradients. The amplitude of the cycle varies between the stations.

The analyzed station 78 is one of the stations with a rather small amplitude, resulting in a comparatively low humidity and high temperature during the night.

In QCSv3 only the absolute humidities are compared. As a result nearly all nightly humidity values at station 78 are falsely flagged in the external reference check. Sporadically, also the old interstational check (maxdiff check) flagged some values.

QCSv4, on the other hand, recognizes the consistency of temperature and humidity and therefore flagged no values at all.

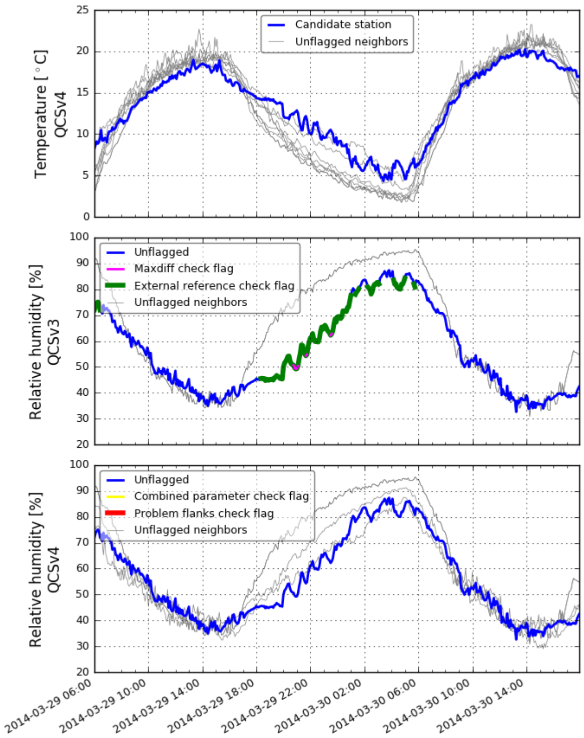


Figure 6.3: Temperature (upper plot), relative humidity from QCSv3 (middle), and relative humidity from Qcsv4 (lower) from March 29, 2014 06:00 UTC to March 30, 2014 18:00 UTC at station 78. Unflagged data are given in blue color. Data flagged in the maxdiff (old interstational check), external reference, combined parameter, and problem flanks checks are given in pink, green, yellow, and red color, respectively. Unflagged data of some neighboring stations are shown in gray color.

6.5.2 Case Study 2: False Alarm of the QCSv3 Interstational Check

Case study 2 covers the time from April 15, 2015 06:00 UTC to April 16, 2015 18:00 UTC and is shown in Figure 6.4.

During the second half of the night, station 27 measured a humidity that was up to 10 %rH higher than the measurements at its neighboring stations. Consequently these values were flagged by the old interstational check in QCSv3.

However, overestimations of humidity are unlikely and a visual inspection of the temporal evolution of humidity and temperature indicates no obvious malfunction. QCSv4 ignores potential overestimations and flagged no values.

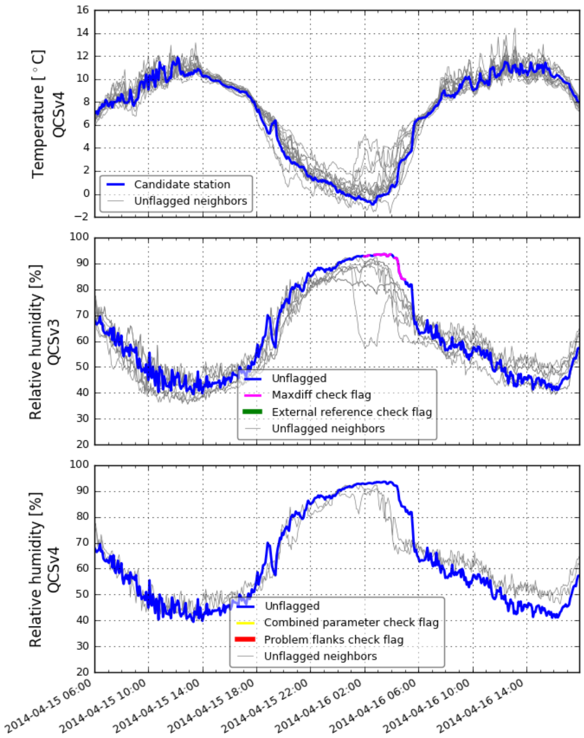


Figure 6.4: Temperature (upper plot), relative humidity from QCSv3 (middle), and relative humidity from Qcsv4 (lower) from April 15, 2014 06:00 UTC to April 16, 2014 18:00 UTC at station 27. Unflagged data are given in blue color. Data flagged in the maxdiff (old interstational check), external reference, combined parameter, and problem flanks checks are given in pink, green, yellow, and red color, respectively. Unflagged data of some neighboring stations are shown in gray color.

6.5.3 Case Study 3: Improved Detection of Problem Behavior

Case study 3 analyzed the timespan from November 01, 2015 06:00 UTC to November 02, 2015 18:00 UTC. It is shown in Figure 6.5. Between 18:00 UTC and 08:00 UTC the humidity is high (>90 %rH) and the variance between the stations is low. At the same time, the humidity at the analyzed station 1 shows exemplary problem behavior. The real value is underestimated by more than 25 %rH.

The external reference check in QCSv3 detects the underestimation late at about 19:00 UTC and considers the values after about 07:00 UTC to be correct again. Due to this mismatch to the real problem behavior episode, underestimations of more than 10 %rH are not detected. The old interstational check (maxdiff check) performs even worse.

In QCSv4 the combined parameter check detects the problem behavior episode almost perfectly.

6.5.4 Case Study 4: Improved Detection of Truncated Values

This case study ranges from August 11, 2015 06:00 UTC to August 12, 2015 18:00 and is shown in Figure 6.6. Temperature and humidity follow a pronounced diurnal cycle. The variance between the stations is rather small.

The analyzed station 65 follows the pattern of its neighbors until about 21:00 UTC. From then on until about 06:00 UTC the time series shows problem behavior. First there is an underestimation of humidity caused by the typical truncation of the humidity peak values. From 00:00 UTC to 05:00 UTC there is an inversed behavior with decreasing measurement values while the real humidity is increasing.

In QCSv3 a small fraction of the underestimations is flagged between 03:00 UTC and 04:00 UTC when the difference from neighbor measurements is largest.

In QCSv4 the underestimations are flagged by the combined parameter check from very start of the truncation at 21:00 UTC until the end of the underestimation at about 06:00 UTC. The inverse behavior is additionally detected by the problem flanks check.

6.5.5 Case Study 5: Improved Detection of Problem Behavior

Case study 5 dates from February 26, 2014 06:00 UTC to February 27, 2014 18:00 UTC and is shown in Figure 6.7.

Starting from about 23:00 UTC, the relative humidity values at station 31 are truncated. From 02:00 UTC to 08:00 UTC there is inverse behavior.

In QCSv3 only the data from 05:00 UTC to 07:00 UTC are flagged by the maxdiff check. Date before and after this time window are not flagged, although the real value is underestimated by up to 20 %rH.

In QCSv4, the truncation and part of the inverse behavior are detected by the combined parameter check and the inverse behavior is entirely flagged by the problem flanks check.

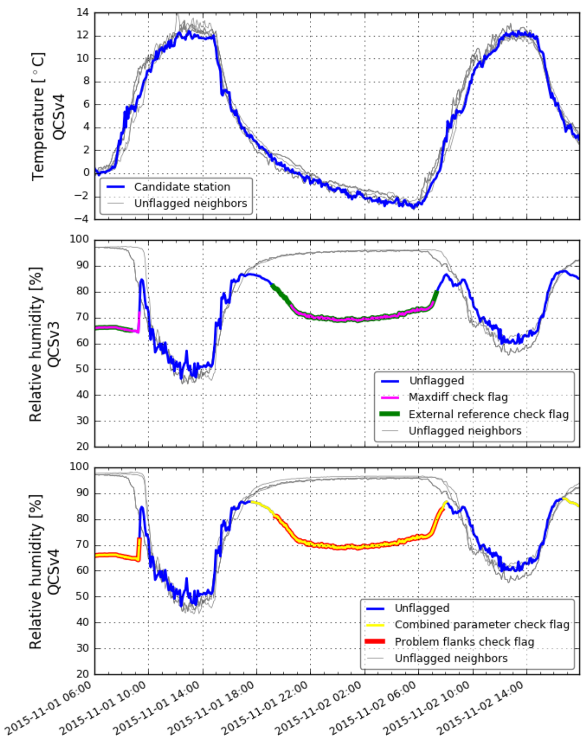


Figure 6.5: Temperature (upper plot), relative humidity from QCSv3 (middle), and relative humidity from Qcsv4 (lower) from November 01, 2015 06:00 UTC to November 02, 2015 18:00 UTC at station 1. Unflagged data are given in blue color. Data flagged in the maxdiff (old interstational check), external reference, combined parameter, and problem flanks checks are given in pink, green, yellow, and red color, respectively. Unflagged data of some neighboring stations are shown in gray color.

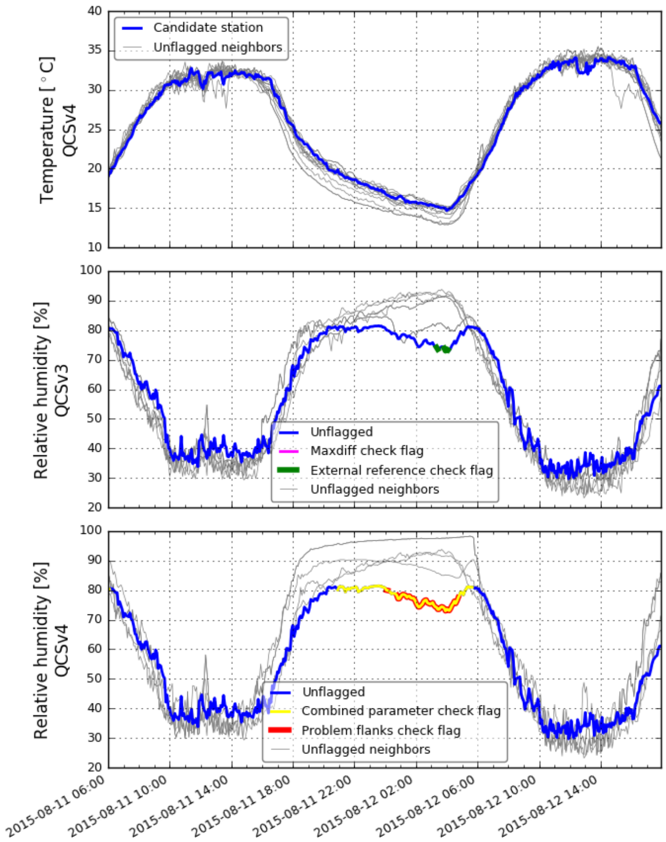


Figure 6.6: Temperature (upper plot), relative humidity from QCSv3 (middle), and relative humidity from Qcsv4 (lower) from August 11, 2015 06:00 UTC to August 12, 2015 18:00 UTC at station 65. Unflagged data are given in blue color. Data flagged in the maxdiff (old interstational check), external reference, combined parameter, and problem flanks checks are given in pink, green, yellow, and red color, respectively. Unflagged data of some neighboring stations are shown in gray color.

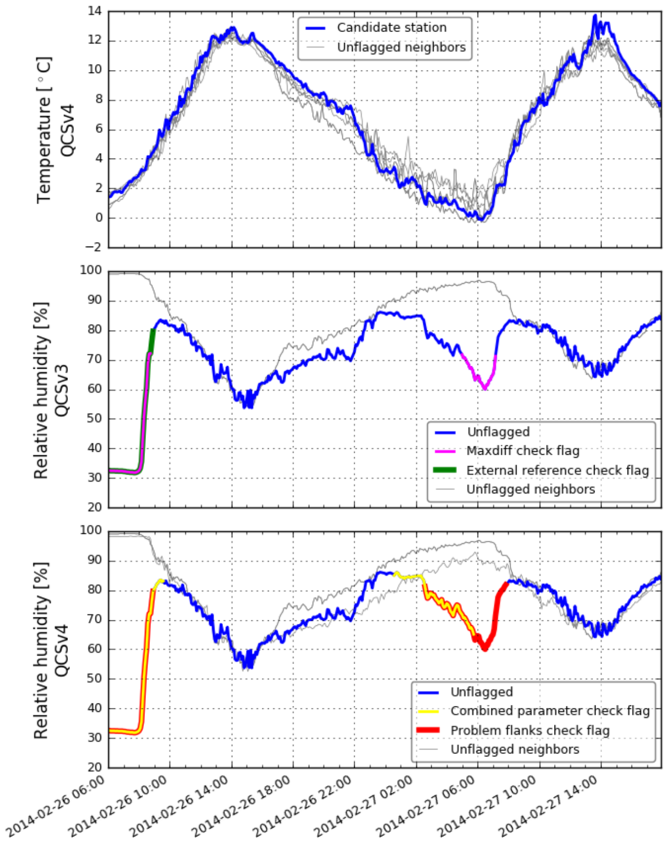


Figure 6.7: Temperature (upper plot), relative humidity from QCSv3 (middle), and relative humidity from QCSv4 (lower) from February 26, 2014 06:00 UTC to February 27, 2014 18:00 UTC at station 31. Unflagged data are given in blue color. Data flagged in the maxdiff (old interstational check), external reference, combined parameter, and problem flanks checks are given in pink, green, yellow, and red color, respectively. Unflagged data of some neighboring stations are shown in gray color.

6.5.6 Case Study 6: False Alarms in Old and New Versions

Case study 6 dates from January 13, 2016 06:00 UTC to January 14, 2016 18:00 and is shown in Figure 6.8. There is a rapid increase of temperature and decrease of humidity at all stations during the mornings. At some stations the temperature decreases and the humidity increases rapidly in the afternoon and remain rather constant during the night. At some other stations there is a slow constant decrease of temperature and increase of humidity from noon until the next morning. The time series of all stations are rather shaky.

The analyzed station 40 follows the later pattern and shows a slightly lower humidity and higher temperature than its neighbors. The pattern is consistent and does not indicate a malfunction.

In QCSv3 there are some random flags from both the old interstational check (maxdiff check) and the external reference check. These flags are due to the fact that they evaluate only humidity and ignore the consistency of the pattern when combined with temperature.

In QCSv4 there are some random flags from the problem flanks check, which are fostered by the noise of the time series.

6.5.7 Comparison of the Fraction of Flagged Data

In another approach to verify the improvements, the humidity data from 2007 to 2015 were reprocessed with the new QCSv4 and the fraction of flagged data in QCSv3 and QCSv4 was compared for the whole period and categorized by months. This comparison was done for all sensors, problem sensors only and "OK" sensors only. A plot is given in Figure 6.9.

The total fraction of flagged data is slightly higher in QCSv4. Compared to QCSv3, the fraction of flagged data generally increased during the winter months, while it decreased during the summer months.

Regarding data from problem sensors, there is a higher fraction of flagged data in QCSv4. It is about 31 % higher than in QCSv3. The difference is particularly large in winter, e.g., nearly 70 % in January. This indicates an improved detection of bad values.

Data from "OK" sensors show a lower fraction of flagged values in QCSv4, indicating a reduced number of false alarms. Regarding the whole processed period, the fraction of flagged data is about 65 % lower than in QCSv3. The difference is slightly larger during the summer months. The most pronounced difference is in April with about 84 %.

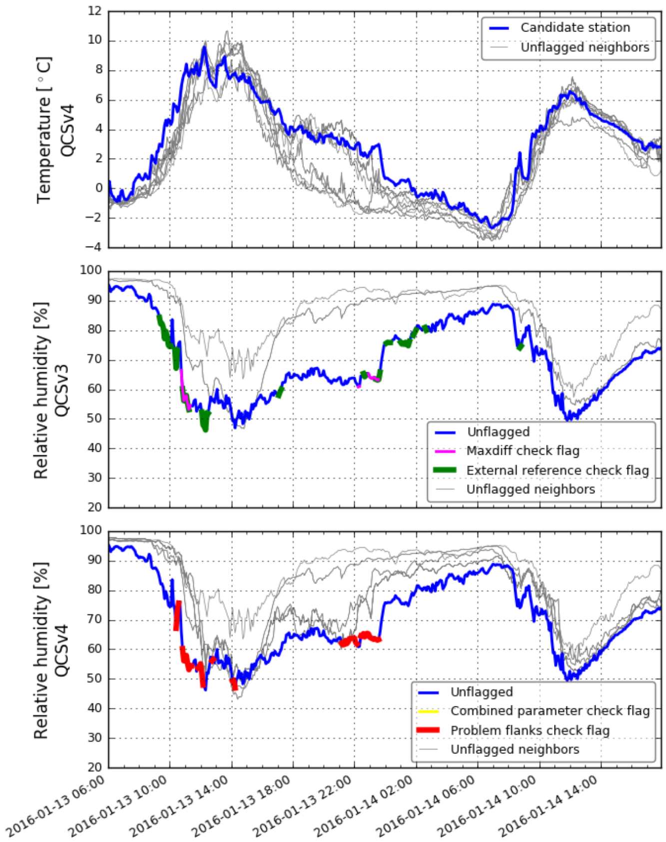


Figure 6.8: Temperature (upper plot), relative humidity from QCSv3 (middle), and relative humidity from QCSv4 (lower) from January 13, 2016 06:00 UTC to January 14, 2016 18:00 UTC at station 40. Unflagged data are given in blue color. Data flagged in the maxdiff (old interstational check), external reference, combined parameter, and problem flanks checks are given in pink, green, yellow, and red color, respectively. Unflagged data of some neighboring stations are shown in gray color.

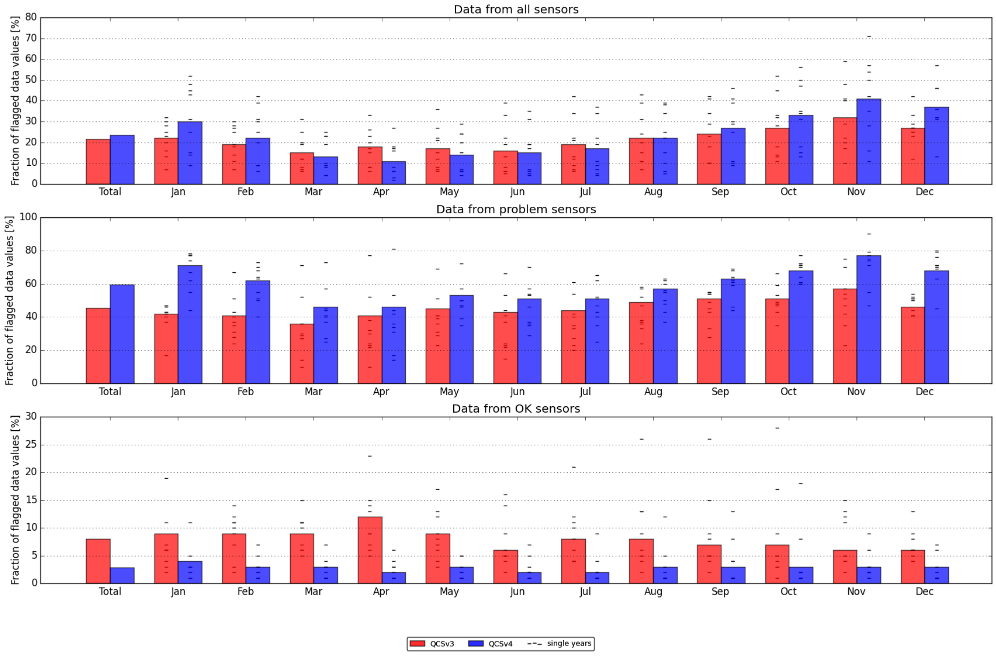


Figure 6.9: Fraction of flagged data values in QCSv4 (red) and QCSv3 (blue) for all data from 2007 to 2015 and according to months. Single year results are indicated by the black horizontal lines. The results are given for all sensors (upper), problem mode sensors (middle) and sensors in status 'OK" (lower).

7 Summary and Conclusions

The objective of this work was to improve the quality of the WegenerNet relative humidity data. The focus hereby was on the detection of a specific kind of malfunction, labeled as problem behavior, causing frequent underestimations.

After a general introduction to the WegenerNet and its quality control procedures, problem behavior was explained and analyzed. The history of dealing with problem behavior and especially the concept of the sensor status were explained. Then two representative cases of problem behavior and the typical performance of the QCS were presented in two case studies. Finally the behavior of different humidity parameters, like specific humidity or mixing ratio, during problem behavior was analyzed. Due to this analysis, an approach to detect problem behavior based on alternative humidity parameters (other than relative humidity) was dismissed, since it would deliver no advantage.

The approach to do interstational comparison not only for humidity measurements, but for a combined parameter comprising humidity and temperature, led to a new criterion for problematic humidity values. This criterion was justified in three case studies and its validity regardless of season or sensor location was proven.

Subsequently, the criterion was developed into an algorithm to automatically assign sensor statuses (*OK* or *problem mode*) on a daily basis. A detailed description of the algorithm and its options was given. The differences between the old, manually assigned, and the new, automatized, sensors statuses were then analyzed and revealed that the automatized statuses are consistent with the general trend of the manual statuses, but show a pronounced annual cycle with a maximum of problem sensors during the winter months.

Most of the times (especially during summer months), the automatized assignment yielded more "OK" sensors than the manual assignment. This can be attributed to the fact that the automatized sensor assignment allows sensors to switch back to "OK" status after a period of problem behavior, while the manual assignment rarely reviewed sensors that were set to problem mode once. The annual cycle reflects the fact that there is generally a higher humidity in winter and therefore problem behavior is more likely then. Case studies further revealed that the automatized assignment detects problem behavior earlier and more reliably than manual inspection. In conclusion, the automatized statuses capture the real sensor performances better than the manual statuses.

Building on this preparatory work, some improvements of the QCS were presented. They comprise a review of the existing time gradient check (resulting in higher allowed 5 minute gradients), a new check implementing the criterion for problematic values (combined parameter check) and a new check detecting the characteristic temporal evolution of an underestimation (problem flanks check).

The performance of the new QCSv4 in comparison to the old QCSv3 was then discussed in five case studies. They showed that the QCSv4 is more sensitive to underestimations. Especially truncations of humidity peaks and transitions from correct values to obvious underestimations (and vice versa) are better identified.

Also the susceptibility for false alarms is reduced due to two reasons: The old algorithm flagged relative humidity values that differed too much from the values at neighboring stations. The new algorithm, on the one hand, allows relative humidity values to be much lower than at the neighboring stations, if the corresponding air temperature is consistently higher. On the other hand, it inherently allows humidity to be higher than at its neighboring stations. This embraces the fact that those values are more likely to be caused by underestimating neighbors than to be overestimations. The problem flanks check is susceptible to false alarms when the temporal variance of humidity is high. But since it is only run for sensors that are in problem mode (i.e. show suspicious behavior), the trade-off seems reasonable.

In addition to the case studies, the fraction of flagged data from 2007 to 2015 was statistically compared for QCSv3 and QCSv4. Overall, there was a slight increase of flagged data. During the winter months the fraction increased, while it decreased during the summer months. Regarding only problem sensors, the fraction of flagged data increased for all months. Regarding only “OK” sensors, the fraction decreased for all months. This analysis further backs the conclusion that the QCSv4 detects relative humidity malfunctions better, while producing less false alarms.

In regard to a follow-up version of the QCS, some possible further improvements are proposed: In principle, the combined parameter check could – with minor modifications – also be applied on air temperature data.

The performance of the combined parameter check seems to depend on the number of neighbor stations used. In QCSv4, neighbors from the next neighborhood level are added until a “wanted number” of five neighbors are available. If less than five neighbors are available from all neighborhood levels, the check is regarded as invalid. While a minimum required number of five neighbors makes good sense, it is proposed to introduce a wanted number of 10 neighbors.

Another proposed improvement of the combined parameter check is to use the next lower value to the median as a reference, instead of the next-higher value to the median. Preliminary tests indicated that this would further decrease the susceptility to false alarms, while yielding an insignificant increase of unflagged bads.

These proposed changes are in principle already implemented into the source code of the QCS and can be eventually used.

Even without those possible improvements, the automatic sensor status assignment proved superior to manual assignment and the new QCS provides a better detection of bad values while producing fewer false alarms.

List of Figures

2.1 Spatial arrangement of the WegenerNet stations. 10

3.1 Relative humidity at station 20 (blue) and selected neighbor stations (grey) for April, July and October 2009. Quality flagged relative humidity values at station 20 are indicated by the red color. 15

3.2 Relative humidity at station 87 (blue) and selected neighbor stations (grey) for October, November and December 2009. Quality flagged relative humidity values at station 87 are indicated by the red color. 16

3.3 Different humidity parameters, saturation vapor pressure, and air temperature at station 20 (blue) and its neighboring stations (grey) and air pressure at station 77 (light blue) from August 17, 2009 09:00 UTC to August 19, 2009 15:00 UTC. Only neighbor data unflagged by the QCS are plotted. 18

4.1 Diagnose plots (upper row) and time series (lower row) for an assumed good sensor (station 37, left column) and a known problem sensor (station 108, right column) from August 15, 2015 09:00 UTC to August 16, 2015 15:00 UTC. The diagnose plots show ΔRH against ΔT (blue) and the criterion threshold (green). The time series show the relative humidity data of the station (red if violating the threshold, otherwise blue), the time-averaged relative humidity data of the station (black) and its reference stations (grey). 22

4.2 Diagnose plots (upper row) and time series (lower row) for an assumed good sensor (station 27, left column) and a known problem sensor (station 3, right column) from December 19, 2015 09:00 UTC to December 20, 2015 15:00 UTC. The diagnose plots show ΔRH against ΔT (blue) and the criterion threshold (green). The time series show the relative humidity data of the station (red if violating the threshold, otherwise blue), the time-averaged relative humidity data of the station (black) and its reference stations (grey). 23

4.3 Diagnose plots (upper row) and time series (lower row) for an assumed good sensor (station 34, left column) and a known problem sensor (station 65, right column) from August 07, 2015 09:00 UTC to August 08, 2015 15:00 UTC. The diagnose plots show ΔRH against ΔT (blue) and the criterion threshold (green). The time series show the relative humidity data of the station (red if violating the threshold, otherwise blue), the time-averaged relative humidity data of the station (black) and its reference stations (grey). 24

4.4 Diagnose plots for January 2015 (upper) and July 2015 (lower) according to the location classes valley (red), middle slope (black) and ridge (blue). The criterion threshold is plotted in green. 26

5.1 Relative humidity at station 19 (blue), measurements of neighboring stations (grey), and assigned sensor status (red; 0: OK, 1: Problem mode) at station 17 from October 12, 2010 to October 25, 2010. 30

5.2 Temporal development of the number of sensors in status “OK” (blue), “problem mode” (red) and “out of operation” (grey) from 2007 to 2016. The manual and automatized assignments are given in dashed and solid line, respectively. 32

5.3 Temporal development of sensor status from automatized assignment (opaque) and manual assignment (transparent) for some selected sensors. The statuses “OK” and “problem mode” are indicated by blue and red color, respectively. 33

6.1 Relative humidity (upper plot) and air temperature (lower plot) at station 130 (blue) and unflagged measurements at neighboring stations from May 28, 2012 to May 29, 2012. 37

6.2 Relative humidity (upper plot) and air temperature (lower plot) at station 130 (blue) and unflagged measurements at neighboring stations from March 25, 2012 to March 26, 2012. 38

6.3 Temperature (upper plot), relative humidity from QCSv3 (middle), and relative humidity from Qcsv4 (lower) from March 29, 2014 06:00 UTC to March 30, 2014 18:00 UTC at station 78. Unflagged data are given in blue color. Data flagged in the maxdiff (old interstational check), external reference, combined parameter, and problem flanks checks are given in pink, green, yellow, and red color, respectively. Unflagged data of some neighboring stations are shown in gray color. 39

6.4 Temperature (upper plot), relative humidity from QCSv3 (middle), and relative humidity from Qcsv4 (lower) from April 15, 2014 06:00 UTC to April 16, 2014 18:00 UTC at station 27. Unflagged data are given in blue color. Data flagged in the maxdiff (old interstational check), external reference, combined parameter, and problem flanks checks are given in pink, green, yellow, and red color, respectively. Unflagged data of some neighboring stations are shown in gray color. 40
6.5 Temperature (upper plot), relative humidity from QCSv3 (middle), and relative humidity from Qcsv4 (lower) from November 01, 2015 06:00 UTC to November 02, 2015 18:00 UTC at station 1. Unflagged data are given in blue color. Data flagged in the maxdiff (old interstational check), external reference, combined parameter, and problem flanks checks are given in pink, green, yellow, and red color, respectively. Unflagged data of some neighboring stations are shown in gray color. 42
6.6 Temperature (upper plot), relative humidity from QCSv3 (middle), and relative humidity from Qcsv4 (lower) from August 11, 2015 06:00 UTC to August 12, 2015 18:00 UTC at station 65. Unflagged data are given in blue color. Data flagged in the maxdiff (old interstational check), external reference, combined parameter, and problem flanks checks are given in pink, green, yellow, and red color, respectively. Unflagged data of some neighboring stations are shown in gray color. 43
6.7 Temperature (upper plot), relative humidity from QCSv3 (middle), and relative humidity from QCSv4 (lower) from February 26, 2014 06:00 UTC to February 27, 2014 18:00 UTC at station 31. Unflagged data are given in blue color. Data flagged in the maxdiff (old interstational check), external reference, combined parameter, and problem flanks checks are given in pink, green, yellow, and red color, respectively. Unflagged data of some neighboring stations are shown in gray color. 44
6.8 Temperature (upper plot), relative humidity from QCSv3 (middle), and relative humidity from QCSv4 (lower) from January 13, 2016 06:00 UTC to January 14, 2016 18:00 UTC at station 40. Unflagged data are given in blue color. Data flagged in the maxdiff (old interstational check), external reference, combined parameter, and problem flanks checks are given in pink, green, yellow, and red color, respectively. Unflagged data of some neighboring stations are shown in gray color. 46
6.9 Fraction of flagged data values in QCSv4 (red) and QCSv3 (blue) for all data from 2007 to 2015 and according to months. Single year results are indicated by the black horizontal lines. The results are given for all sensors (upper), problem mode sensors (middle) and sensors in status 'OK" (lower). 47

List of Tables

2.1 Location classes of WegenerNet stations. 11
2.2 Neighborhood levels for relative humidity 12

3.1 List of sensor statuses 14

4.1 Extended neighborhood levels for relative humidity 19
4.2 Case studies for different weather conditions 21
4.3 Station numbers of selected, assumedly good sensors according to location class. 25

5.1 Script options 28

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Abstract:
The WegenerNet Feldbach Region is a network of 154 meteorological stations (status December 2017), providing data with a temporal resolution of five minutes and a spatial resolution of about 1.4 km. The data quality is ensured by a number of automatized quality checks, subsumed in the Quality Control System (QCS).
In this work distinctive malfunctions of the relative humidity sensors of the WegenerNet are addressed. The sensors frequently showed episodes of problematic behavior, during which values above a certain threshold were truncated or showed “inverse behavior”. Until now, the detection of problem behavior was largely dependent on manual inspection because it was not adequately recognized by the QCS. The objective of this work was to analyze this problem behavior and to improve the procedures and QCS algorithms, such that problem behavior is automatically identified.
The main approach was to set up a criterion for problematic humidity values based on an interstational comparison of relative humidity and air temperature. First, this criterion was embedded into an algorithm to automatically identify problem sensors on a daily basis. A verification revealed that the algorithm is more reliable and more accurate than manual inspection. Then the criterion was implemented in the QCS to check individual humidity values.
Additionally, some further improvements of the QCS were done, including another quality check based on the characteristic temporal evolution of problem behavior. Case studies and a statistical analysis verified that the new QCS version has an improved detection of problematic values, while producing less false alarms.

Zum Inhalt:
Das WegenerNet Region Feldbach ist ein Netzwerk von 154 meteorologischen Stationen (Stand Dezember 2017), das Daten mit einer zeitlichen Auflösung von fünf Minuten und einer räumlichen Auflösung von ca. 1,4 km liefert. Die Datenqualität wird durch verschiedene automatisierte Plausibilitätsprüfungen gewährleistet, die im Quality Control System (QCS) zusammengefasst sind.
Die vorliegende Arbeit befasst sich mit der Erkennung des Problemverhaltes der WegenerNet Feuchtesensoren. Die Sensoren zeigten häufig Episoden von problematischem Verhalten, bei denen Werte oberhalb einer bestimmten Schwelle abgeschnitten wurden oder sogar „inverses Verhalten“ auftrat. Bisher war die Erkennung solchen Problemverhaltens weitgehend von einer manuellen Überprüfung abhängig, da es vom QCS nicht adäquat detektiert wurde.
Ziel dieser Arbeit war es, das Problemverhalten zu analysieren und die Verfahren und QCS-Algorithmen so zu verbessern, dass das Problemverhalten automatisch erkannt und falsche Werte im QCS identifiziert werden. Dazu wurde ein Kriterium aufgestellt, das problematische Feuchtigkeitswerte durch einen Vergleich der relativen Feuchte und der Lufttemperatur mit Nachbarstationen erkennen soll. Dieses Kriterium wurde in einen Algorithmus eingebettet, der anhand der Daten eines Tages bewertet ob Problemverhalten an einem Sensor vorliegt. Eine Auswertung ergab, dass dieser Algorithmus zuverlässiger und genauer ist als die bisherige manuelle Sichtung. Daher wurde das Kriterium in einen QCS-Test implementiert, wo es auf einzelne Feuchtewerte angewandt wird.
Darüber hinaus wurden einige weitere Verbesserungen des QCS durchgeführt. Unter anderem wurde ein weiterer Test implementiert, der sich die charakteristische zeitliche Entwicklung des Problemverhaltens zunutze macht. Einige Fallstudien und eine statistische Analyse bestätigten, dass die neue QCS-Version das Problemverhalten besser erkennt und gleichzeitig weniger falsche Alarme liefert.

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ISBN 978-3-9504501-2-5