Validation and correction of rainfall data from the WegenerNet high density network in southeast Austria

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ABSTRACT

Eight years of daily rainfall data from WegenerNet were analyzed by comparison with data from Austrian national weather stations. WegenerNet includes 153 ground level weather stations in an area of about 15 km × 20 km in the Feldbach region in southeast Austria. Rainfall has been measured by tipping bucket gauges at 150 stations of the network since the beginning of 2007. Since rain gauge measurements are considered close to true rainfall, there are increasing needs for WegenerNet data for the validation of rainfall data products such as remote sensing based estimates or model outputs. Serving these needs, this paper aims at providing a clearer interpretation on WegenerNet rainfall data for users in hydro-meteorological communities.

Five clusters – a cluster consists of one national weather station and its four closest WegenerNet stations – allowed us close comparison of datasets between the stations. Linear regression analysis and error estimation with statistical indices were conducted to quantitatively evaluate the WegenerNet daily rainfall data. It was found that rainfall data between the stations show good linear relationships with an average correlation coefficient (r) of 0.97, while WegenerNet sensors tend to underestimate rainfall according to the regression slope (0.87). For the five clusters investigated, the bias and relative bias were −0.97 mm d⁻¹ and −11.5% on average (except data from new sensors). The average of bias and relative bias, however, could be reduced by about 80% through a simple linear regression-slope correction, with the assumption that the underestimation in WegenerNet data was caused by systematic errors. The bias, however, could be reduced by about 80% through a simple linear regression-slope correction, with the assumption that the underestimation in WegenerNet data was caused by systematic errors. The results from the study have been employed to improve WegenerNet data for user applications so that a new version of the data (v5) is now available at the WegenerNet data portal (www.wegenernet.org).

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1. Introduction

Rainfall data are essential for a large number of applications. The data provide inputs for understanding and modeling of heavy rainfall, floods and landslides (Hong et al., 2007; Medlin et al., 2007), offer information for relevant applications such as agriculture and urban drainage systems (Ines and Hansen, 2006; Villarini et al., 2010) and add insights across sectors, for example, health and insurance (Hellmuth et al., 2009; Kirschbaum, 2016). Such rainfall data can mainly be obtained from gauge measurements or remote sensing based observations, e.g., radars and satellites, although it is difficult to obtain the data without introducing systematic errors and other uncertainties (Sevruk, 2005; AghaKouchak et al., 2012; Kirstetter et al., 2012).

Despite recent developments in rainfall estimations using remote sensing techniques, to overcome spatial coverage limitations in rain gauge data, such ground level gauges remain the true reference since they are the only instruments that give direct measurements of rainfall. The data from rain gauges have been merged into radar or satellite algorithms to optimize their rainfall information (Adler et al., 2000; Sinclair and Pegram, 2005; Vila et al., 2009; Nerini et al., 2015), and have also been used to validate rainfall datasets produced from remote sensing observations (Bringi et al., 2011; Worrilul et al., 2014). Therefore, the availability of proper ground networks is one of the key factors to obtain more accurate rainfall estimations for remote sensing communities (Habib and Krajewski, 2002; Krajewski et al., 2010; Kneis et al., 2014; Sharifi et al., 2016). For example, the NASA Precipitation Measurement Missions (PMM) project has operated a ground val-
WegenerNet data is increasing as more communities request the data. Moreover, the need for a careful performance evaluation of the WegenerNet precipitation data has been highlighted (Kirchengast et al., 2014). However, there has been little consideration given to quantitative assessment of the WegenerNet precipitation data. The latter system has also been evaluated for temperature, humidity, and wind speed using WegenerNet measurements data (Kann et al., 2015). The region is in the Alpine foreland shielded by the mountain crest so the climate is more heavily influenced by Mediterranean climate systems. This leads to mild winters, hot summers, and summer precipitation dominated by heavy rain from thunderstorms (Kabas et al., 2011; Strauss et al., 2013; Denk and Berg, 2014). After the beginning of regular measurements in 2007, precipitation data have been used for applications such as the study of small-scale rainfall events (Kabas et al., 2011) and for the evaluation of precipitation analyses of the Austrian operational nowcasting system, INCA (Kann et al., 2015). The latter system has also been evaluated for temperature, humidity, and wind speed using WegenerNet measurements data (Kann et al., 2011). However, there has been little consideration given to quantitative assessment of the WegenerNet precipitation data. Moreover, the need for a careful performance evaluation of the WegenerNet data is increasing as more communities request the data as a valuable ground validation reference, as did the NASA PMM Science Team recently (Fuchsberger et al., 2015).

When precipitation data from rain gauges are used as reference data in research, the main concern is related to uncertainties in the accuracy of areal estimates, which stem from the limited spatial representativeness of the gauges (Villarini et al., 2008). In this study, however, the investigation on agreements with operational gauges in sub-areas is given priority over the study of the whole domain of the WegenerNet network. A spatially uniform and high resolution configuration of the WegenerNet implies that it is less likely to suffer from uncertainties in terms of spatial resolution (Morrissey et al., 1995). Moreover, we are operating our maintenance team not only for data quality control but also for on-site routine tasks in the field to assure that the WegenerNet can rather be used as a reference to evaluate the uncertainties in other rainfall data for the same domain. Additionally, according to Tokay et al. (2010), who compared rainfall data between various types of gauges, it is recommendable to report the findings from certain gauge networks so that users or network organizers can have the knowledge of a particular gauge type or a network.

The main objective of this study is to quantitatively evaluate WegenerNet daily rainfall data through careful comparison with data from Austrian national weather stations. Based on the results, this study suggests a linear correction factor to decrease bias in the WegenerNet data. The datasets used in the study are introduced in Section 2. Section 3 describes the research setup, including data preparation. Section 4 presents results and discussion of data analysis and correction. Finally, we conclude by summarizing the main results and discussing considerations for the use of WegenerNet data.

2. Data

2.1. WegenerNet

Fig. 1 shows the WegenerNet Feldbach region network with the 153 weather stations at which precipitation is measured with tipping bucket gauges (Serruk, 1996; Pavlyukov, 2007). The region is characterized by the river Raab valley and a moderate hilly landscape ranging from 257 m to 609 m. The network was developed in 2006, with the station locations carefully selected to be representative for their local area amongst the neighbor station areas and to be influenced by no or minor nearby obstacles, and has been providing station and gridded datasets of temperature, precipitation, humidity and other parameters since January 2007 (data are available at http://www.wegener.net). The WegenerNet and its datasets have already been described in detail by Kirchengast et al. (2014), so we will only focus on explaining precipitation measurements as we use and evaluate them in the context of this study.

Integrated precipitation amount is sampled every five minutes at each station. Raw measurements are checked for technical and physical plausibility through a Quality Control System (QCS) (Scheidl, 2014; Szeberenyi, 2014) (called level 1 data) and are then interpolated and summed up to produce level 2 precipitation data products for a range of time scales from sub-daily starting at 5 min to annual; level 2 daily data are used in this study. WegenerNet employs three different types of sensors; a reference station employs all three sensors; and 11 primary stations are equipped with a sensor with heating system so that they can measure solid precipitation (see also Appendix A for details). Currently, the sensor type in use for these stations is Kroneis MeteoServis type MR3H, hereafter referred to as “Meteo” (Meteo, 2016). Note that the stations had R.M. Young model 52202 gauges, hereafter “Young” (Young, 2016), until October 2013, when they were all replaced by Meteo sensors. The majority of stations (138) are base stations, which were equipped with a sensor of Theodor Friedrichs & Co. model 7041.2000 until 2016, hereafter “Friedrichs” (Friedrichs, 2016), without a heating system. Since recently, after a replacement project for the Friedrichs sensors within 2016, all base stations are equipped with Meteo sensors (see Section 5).

2.2. Reference stations

Precipitation data collected from weather stations operated by the Central Institute for Meteorology and Geodynamics (ZAMG) and by the Austrian Hydrographic Service (AHYD) were selected as reference data because of their reliability. ZAMG operates a network of semi-automatic stations across the country, and AHYD operates a hydrometeorological network, both providing quality controlled precipitation data. The data from these networks have been used for official records of Austrian precipitation data and have enabled the operation of the INCA system in Austria (Rudel, 2008; Haiden et al., 2009, 2011).

The geographic locations of two ZAMG and three AHYD stations in the study area are shown in Fig. 1. The ZAMG stations have tipping bucket gauges with a sensor of Anton Paar model AP-23, hereafter “Paar” (Paar, 2016), equipped with a heating system. Both 10-min and daily precipitation data are available. AHYD stations provide precipitation data by manual measurement with a daily temporal resolution, termed “manual” hereafter. Each station is named in this paper by its official number, as annotated in Fig. 1.

3. Research setup

3.1. Data preparation

Daily data for the eight-year period from 2007 to 2014 were used in this study. Given that a gauge can represent rainfall measurements for a limited spatial extent only, WegenerNet stations near each reference were selected for comparison (see Fig. 1 (right panel)). Five clusters, each comprised of one reference station and
the four closest WegenerNet stations, are defined. The average distance between a WegenerNet station and its reference station is around 1.02 km, ranging from 0.23 to 2.75 km. Each cluster is labeled with the name of the reference station. Table 1 lists the selected stations along with information on their data. Note that for WegenerNet stations, level 2 data from version 4 were used. We considered only pairs of daily rainfall amount data for which WegenerNet and reference station values are both non-zero and non-missing. Additionally, WegenerNet data lower than 0.2 mm d\(^{-1}\) and reference data lower than 0.1 mm d\(^{-1}\) were deleted to avoid false alarms at very low intensities. Finally, solid precipitation data were excluded; this will be addressed later in

![Fig. 1](image-url) (a) Map of WegenerNet, ZAMG, and AHYD (black dots, red rectangles, and orange diamonds, respectively) stations in the Feldbach Region, Austria. (b) Location of five clusters used in the study. A cluster is defined as a group of one reference station (ZAMG or AHYD station) and the four closest WegenerNet stations. The stations are labeled by their official number.

Table 1

General description of weather stations and rainfall datasets, from 2007 to 2014, used in the study. Reference stations of ZAMG (Z) and AHYD (H) are printed in bold. \(D_{\text{ave}}, D_{\text{std}},\) and \(D_{\text{max}}\) denote the average, standard deviation, and max value of each dataset.

| Station | Latitude [°N] | Longitude [°E] | Altitude [m] | Sensor type | Descriptive statistics [mm d\(^{-1}\)] |
|---------|---------------|---------------|--------------|-------------|---------------------------------------|
| H4102   | 46.994        | 15.874        | 303          | Manual      | 7.63 9.44 54.84                      |
| W006    | 46.997        | 15.855        | 398          | Friedr.     | 6.98 8.80 54.30                      |
| W007    | 46.994        | 15.871        | 308          | Friedr.     | 7.63 9.60 62.60                      |
| W008    | 46.996        | 15.886        | 363          | Friedr.     | 7.23 9.17 65.87                      |
| W015    | 46.983        | 15.871        | 297          | Friedr.     | 6.98 8.30 54.30                      |
| H4100   | 46.978        | 15.816        | 306          | Manual      | 7.63 9.44 54.84                      |
| W011    | 46.981        | 15.780        | 300          | Young – Meteo | 6.81 8.02 48.44                   |
| W012    | 46.983        | 15.814        | 370          | Friedr.     | 7.94 8.95 49.80                      |
| W013    | 46.984        | 15.835        | 311          | Friedr.     | 8.94 10.02 54.36                     |
| W027    | 46.972        | 15.815        | 298          | Friedr.     | 6.98 8.30 54.30                      |
| H4150   | 46.933        | 16.018        | 260          | Manual      | 7.58 9.41 65.19                      |
| W068    | 46.946        | 16.023        | 257          | Friedr.     | 7.31 9.76 68.72                      |
| W082    | 46.933        | 16.003        | 276          | Young – Meteo | 8.21 10.15 81.83                  |
| W083    | 46.935        | 16.023        | 274          | Friedr.     | 7.25 8.99 79.10                      |
| W098    | 46.920        | 16.021        | 318          | Friedr.     | 7.19 9.50 66.48                      |
| Z205    | 46.949        | 15.880        | 323          | Paar        | 6.81 8.52 66.13                      |
| W045    | 46.954        | 15.876        | 289          | Friedr.     | 6.81 9.20 69.70                      |
| W046    | 46.955        | 15.886        | 280          | Friedr.     | 6.75 9.07 65.48                      |
| W060    | 46.943        | 15.877        | 351          | Friedr.     | 6.65 8.87 60.10                      |
| W061    | 46.944        | 15.889        | 322          | Friedr.     | 6.65 8.87 60.10                      |
| Z204    | 46.872        | 15.904        | 269          | Paar        | 6.81 8.52 66.13                      |
| W134    | 46.879        | 15.888        | 316          | Young – Meteo | 6.75 9.02 60.58                   |
| W135    | 46.881        | 15.909        | 305          | Friedr.     | 6.86 8.87 50.13                      |
| W144    | 46.867        | 15.890        | 269          | Friedr.     | 5.58 7.37 53.50                      |
| W145    | 46.868        | 15.907        | 279          | Friedr.     | 5.58 7.37 53.50                      |

Young sensors were replaced by Meteo sensors during October 2013.
Section 4.1. Note that the descriptive statistics in Table 1 are calculated from the datasets after all data preparation steps.

3.2. Analyses

We first compared data between WegenerNet and reference stations using scatter plots with a regression line through the origin (Eisenhauer, 2003) to determine the general behavior of the WegenerNet stations. Let $W_i$ and $R_i$ be the data from WegenerNet and the reference station, respectively, at the $i$th day. The slope of the regression line can be expressed as

$$\text{slope} = \frac{\sum_{i=1}^{N} (W_i - R_i)}{\sum_{i=1}^{N} R_i^2},$$  (1)

where $N$ is the number of available paired daily datasets. The Pearson correlation coefficient between the data is given by

$$r = \frac{\sqrt{\sum_{i=1}^{N} W_i^2 / \sum_{i=1}^{N} W_i^2}}{\sum_{i=1}^{N} R_i^2 / \sum_{i=1}^{N} R_i^2},$$  (2)

where $\bar{W}_i$ is the $i$th fitted value of WegenerNet data from the linear regression line fit.

Considering the purpose of the study to provide information for WegenerNet data users, we selected widely used statistical indices for evaluating the data. Bias ($\text{bias}$) and mean absolute error ($\text{MAE}$) are computed according to Eqs. (3) and (4). Relative bias ($\text{rbias}$) and relative mean absolute error ($\text{rMAE}$) are similar to the $\text{bias}$ and $\text{MAE}$, but they are relative values with respect to the reference values according to Eqs. (5) and (6). The root mean squared error (RMSE) is defined per Eq. (7).

$$\text{bias} = \frac{\sum_{i=1}^{N} (W_i - R_i)}{N},$$  (3)

$$\text{MAE} = \frac{\sum_{i=1}^{N} |W_i - R_i|}{N},$$  (4)

$$\text{rbias} = \frac{\left( \sum_{i=1}^{N} (W_i - R_i) \right) / \left( \sum_{i=1}^{N} R_i \right) \times 100}{},$$  (5)

$$\text{rMAE} = \frac{\left( \sum_{i=1}^{N} |W_i - R_i| \right) / \left( \sum_{i=1}^{N} R_i \right) \times 100}{},$$  (6)

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^{N} (W_i - R_i)^2}{N}}.$$  (7)

4. Results and discussion

4.1. Data availability

After preliminary analyses of errors in the WegenerNet data, only data with a zero quality flag (hereafter q0) were selected for the study. The q0 flag means that the data passed the QCS without errors (Kabas et al., 2011; Kirchengast et al., 2014). The upper part of Table 2 shows the percentage of WegenerNet precipitation data for each quality flag over the study period. The lower availability of q0 data during the winter is caused by solid precipitation measurements. Since only 12 stations are heated, all other stations get interpolated values for solid precipitation. Those data are marked by a quality flag of “3” or “4”, which indicate “data interpolated spatially from closest points in derived grid data” and “missing values due to a lack of sufficient data for the spatial interpolation”, respectively. For further information on the quality flags, see Appendix A.

To avoid “artificial” errors by solid precipitation measurements, we decided to focus on WegenerNet data collected on days with a minimum temperature above 2°C. Therefore, we will refer to the data used in this study as “rainfall” rather than more generally as “precipitation”.

As a result, the availability of q0 data is calculated to be more than 95% for the five clusters as well as for the whole WegenerNet network as summarized in the lower part of Table 2. Around 660 daily records (the total amount of rainfall is 4747 mm for the study period) at each station could be used in the study after data preprocessing: before the exclusion of solid precipitation, the number of rainy-day data was around 710 records (the total amount of precipitation was 4961 mm) at each station. The number of available data is larger from April to October, around 96%. It encompasses the rainy season of Austria in which the high spatial resolution network is of special interest. In addition, it was found that data with a non-zero quality flag have larger errors or exceptionally large errors under specific weather conditions such as heavy snowfall. The details are addressed for background information in Appendix A.

4.2. Data comparison

Fig. 2 shows a direct comparison of the daily and accumulated rainfall data over the study period at three exemplary clusters (H4100, Z244, and Z298) to give a first impression of the data characteristics. The paired datasets follow a similar inter-annual and annual variability and well describe an annual rainfall pattern in the recent past, including the story of 2009 summer rainfall when southeast Austria suffered from heavy rainfall events.

Although there is a fair correspondence between datasets, it can be seen from the accumulated rainfall and the peaks of daily rainfall that WegenerNet generally depicts lower rainfall records than the reference stations. The other two clusters (not shown) confirm a similar underestimation behavior in the WegenerNet data.

Fig. 3 displays a linear regression through the origin along with the Q-Q (quantile-quantile) plots to quantify the underestimates. The slope ($\text{slope}$), correlation coefficient ($r$) of the linear regression, and the number of data used ($n$), are specified in each plot. The rainfall data show a good correlation with the scattered data along the linear function, but the WegenerNet sensors tend to underestimate the rainfall in all the stations investigated. The $\text{slope}$ ranges from 0.81 to 0.98 except for station W145 (0.70), which somehow yielded particularly poor agreement with its reference. The average of the underestimation factor ($\text{slope}$) is 0.87. The analysis also indicates that the data from the Friedrichs sensors are in closer agreement with the reference data compared to those from the Young sensors, although only three Young sensor stations were included in the study. The Young sensors show an average $\text{slope}$ of 0.82, while the Friedrichs sensors show 0.88. The difference in the slope value could be attributed to a systematic error between different sensor types, in fact Young sensors feature the smallest catching area compared with the other sensors (catching area of Young sensor is 200 cm² while Friedrichs and Meteo sensor have 211 and 500 cm², respectively), which likely contributes to the undercatch of actual rain amounts. Or, it could be due to the fact that Young sensors were partially blocked more often, e.g., by leaves, insects, or pollen, we assume, however, that such bad data were removed by selecting only the q0 data in Section 4.1.

The scatter plots reveal that the correlation between the WegenerNet and reference data is strong for all clusters, regardless of sensor type. The correlation coefficient ranges from 0.93 to 0.99, averaging about 0.97. Based on this high correlation coefficient...
Table 2
Description of quality flags and the number of WegenerNet precipitation data flagged in each month. Only rainfall data were considered separately in the lower table. \( N_{\text{all}} = \) percentage of data [%] for the whole WegenerNet network, \( N_{\text{clu}} = \) percentage of data [%] for the five clusters investigated. Bold numbers indicate the best quality data.

| Flag | Percentage of daily precipitation data flagged [%] | \( N_{\text{all}} \) | \( N_{\text{clu}} \) |
|------|--------------------------------------------------|----------------|----------------|
| q0   | 16.7 21.6 58.8 93.2 96.5 96.0 95.4 94.8 95.8 83.8 61.7 20.8 | 69.8 | 69.3 |
| q1   | 15.9 20.2 19.5 3.2 0.6 0.6 0.6 0.7 0.8 10.8 11.0 18.6 8.5 | 8.8 |
| q2   | 14.1 15.0 8.9 2.3 2.9 3.4 4.0 4.5 3.0 4.1 12.8 15.8 7.5 | 8.0 |
| q3   | 18.5 16.2 5.8 0.8 0.0 0.0 0.0 0.0 0.0 1.1 7.6 25.3 6.2 | 6.0 |
| q4   | 34.9 27.0 6.9 0.5 0.0 0.0 0.0 0.1 0.3 0.2 7.0 19.6 8.0 | 7.9 |

| Flag | Percentage of daily rainfall data for days with \( T_{\min} \leq 2 \, ^{\circ}\mathrm{C} \) [%] | \( N_{\text{all}} \) | \( N_{\text{clu}} \) |
|------|--------------------------------------------------|----------------|----------------|
| q0   | 90.8 93.0 95.7 97.5 96.6 96.0 95.4 94.8 96.1 96.5 93.9 90.5 95.7 | 95.2 |
| q1   | 6.9 3.9 1.8 0.4 0.5 0.6 0.6 0.7 0.8 0.9 1.2 4.5 0.9 | 1.0 |
| q2   | 2.3 3.1 2.5 2.1 2.9 3.4 4.0 4.5 3.0 2.6 4.9 5.1 | 3.4 |
| q3   | 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 | 0.0 |
| q4   | 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 | 0.0 |

q0 = data which have passed all quality checks without errors.
q1 = data interpolated temporally within station time series.
q2 = data interpolated spatially from defined neighboring stations.
q3 = data interpolated spatially from closest points in derived grid data.
q4 = missing values.

Fig. 2. Time series of daily rainfall data [mm d\(^{-1}\)] and daily accumulated rainfall data [mm] (right-hand-side axis) from 2007 to 2014 at the example clusters of H4100, Z244, and Z298.
between the datasets, the underestimation can be regarded as a systematic error due to different gauge or sensor types. In addition, the Q-Q plots which lie along regression lines show that the linear relationship remains the same in different rain intensity ranges.

The change in data agreement due to sensor replacements is represented in Fig. 4. Stations W011, W082, and W135, which are currently equipped with Meteo sensors, had Young sensors before October 2013. Along with the other stations equipped with Friedrichs sensors, a linear regression was conducted for each station using data separately before and after the sensor replacements. There has been considerable improvement in the data agreement between WegenerNet and reference stations after the Meteo sensors started reporting their measurements, as the average slope jumped from 0.82 to 0.96. On the other hand, the Friedrichs stations do not show any significant improvement as expected. We may need more sampling from the Meteo sensors for a longer period to make a fairly firm conclusion. Nevertheless, the result provides strong evidence of higher reliability of these new Meteo sensors. Additionally, the improvement in the agreement between the datasets after installing better sensors provided added confidence in the ZAMG and AHYD data as a reference.

While checking the outliers in the scatter plots, we found cases such as the one shown in Fig. 5, which can highlight the advantage of the high spatial resolution of the network in spite of the underestimation behavior in the sensors. On 8 May 2007, when daily rainfall was recorded as 7.6 mm and 16.4 mm by Z244 and the
WegenerNet stations in the cluster, respectively, a short-term rain-
fall event occurred during 20 min; Z244 recorded missing values
while the WegenerNet stations recorded 5.0 mm and a maximum
of 3.4 mm (5 min)^{-1} (at station W134) during the event. Under
normal circumstances, we have to rely on the information from
the ZAMG station. On the other hand, WegenerNet can provide
more reliable data in terms of spatial uncertainty. First, the high
spatial resolution can overcome the under-sampling issue, as con-
firmed graphically in the figure. Second, instantaneous errors at a
station can be corrected through the consistency check between
the stations. Therefore, the WegenerNet network will be particu-
larly valuable to study the intensity and structure of small scale
convective rainfall systems.

4.3. Error analysis

The level of agreement between WegenerNet and reference sta-
tion data is measured for each month through bias, rbias, MAE,
Fig. 5. Spatio-temporal distribution (gridded by an inverse-distance weighted interpolation method) of WegenerNet network rainfall records [mm (5 min)\(^{-1}\)] on 8 May 2007 between 19:10 and 19:30 UTC. The red rectangle is the Z244 station and black dots show its closest four WegenerNet stations.

Fig. 6. bias, rbias, MAE, rMAE, and RMSE of the WegenerNet daily rainfall data compared with their reference stations for each month. Values from all 20 WegenerNet stations are plotted in red, the distribution is shown by box-and-whisker plots.
rMAE, and RMSE as defined by Eqs. (3)–(7) after removing outliers, as shown in Fig. 6. We removed the outliers based on rMAE so as to eliminate errors which probably resulted from unusual cases such as sensor failure rather than systematic differences between the stations. The distribution of rMAE was calculated using all data from each sensor type (e.g. data from three stations were combined to calculate rMAE of Young) and then two criteria were considered to define outliers. First, a WegenerNet station in a cluster showed rMAE higher than the 95th percentile (which was 100.0% for the Friedrichs and 94.3% for the Young sensor) but the other three stations did not. Second, rMAE was higher than the 80th percentile at all four WegenerNet stations in a cluster (41.7% for the Friedrichs and 51.7% for the Young sensor).

As expected, the average bias shows a negative value, amounting to −0.84 mm d⁻¹. The rbias ranges from −6.9% (in January) to −12.1% (in July), averaging −10.1%, which shows that monthly rbias lies within a certain limited range of values. The averages of MAE, rMAE, and RMSE are 1.37 mm d⁻¹, 16.5%, and 2.33 mm d⁻¹, respectively.

The monthly averages MAE, rMAE, and RMSE range from 0.72 to 2.17 mm d⁻¹, from 11.9 to 19.9%, and from 0.95 to 3.85 mm d⁻¹, respectively. Large values for MAE and RMSE (1.75 mm d⁻¹ and 3.19 mm d⁻¹ on average) appear during May–September. During the summer season, the dominant rainfall type in the region is often a convective system associated with high rain rates, which can lead to higher MAE and RMSE during this season.

Some high error values were investigated in detail. First, the data from December to February show a wider range of errors or a different behavior (e.g., positive bias) that is probably due to the small number of available records during the winter season, sometimes less than 10 daily datasets at a station for a month. Next, the W145 station has relatively high errors; for example, sometimes less than 10 daily datasets at a station for a month.

The fundamental concept of the correction is to apply a correction factor (a), defined as the inverse of one common slope of the linear regression between datasets from all 19 WegenerNet stations, except W145, and the corresponding reference stations. The linear regression function to predict (correct) toward “true” values was calculated for Friedrichs and Young separately, as shown in Table 3. Meteo sensors were not included in the correction procedure, since they had been found to have the same quality level as the reference stations without correction (see Fig. 4). The form of the simple correction is as follows:

\[ X' = a \cdot X \]  

where a is the inverse of slope, X is the rainfall intensity (mm d⁻¹) measured by WegenerNet stations before the correction and X’ is the bias-corrected rainfall intensity (mm d⁻¹).

Fig. 7 shows bias, rbias, and slope before and after the correction at each station for all five clusters. Related average numbers are shown in Table 4. Before the correction, the average of bias, rbias, and slope had values of −0.97 mm d⁻¹, −11.5%, and 0.87, respectively. Station W027 is the only one having a positive bias of 0.28 mm d⁻¹, which is the smallest bias in absolute terms. This station also has the best agreement with its reference according to the scatter plot in the previous section (Fig. 3). The average values of bias and rbias of Meteo data (no correction) are −0.30 mm d⁻¹ and −3.1%, respectively.

After applying the correction factor, the accuracy of WegenerNet rainfall data improved in terms of both bias and rbias, which decreased to −0.20 mm d⁻¹ and to −2.5% on average, respectively. The average of the slope also improved by about 10% (from 0.87 to 0.96), which is much closer to the one-to-one line. On the other hand, some stations like W027 and W006 were overcorrected, but positive results clearly dominate.

5. Conclusions

The main purpose of the study was to provide insight into WegenerNet daily rainfall data regarding general data characteristics and their associated errors. Therefore we undertook to characterize WegenerNet precipitation data through comparison and error analyses against precipitation data from national weather stations. The comparison, conducted in five station clusters of four WegenerNet and one reference station each, showed good agreement between the datasets but also that the WegenerNet stations somewhat underestimate rainfall amounts. The underestimates of WegenerNet data contribute to a negative bias and relative bias, which have values of −0.97 mm d⁻¹ and −11.5%, respectively. Such underestimation applies to the Friedrichs and Young sensor data in WegenerNet; the Meteo sensor data are in good agreement with the reference stations. Along these lines, we found a clear improvement in the data agreement with the reference stations after replacement of Young by Meteo sensors at some of WegenerNet stations. To mitigate the biases of around 12% from the Friedrichs and Young sensors, we derived simple bias correction factors based on the regression-line slope calculated by all data.

### Table 3

| Sensor Type | Correction Factor (a) | Regression Coefficient (r) |
|-------------|-----------------------|---------------------------|
| Friedrichs  | 1.10                  | 0.98                      |
| Young       | 1.13                  | 0.97                      |
| Meteo       | –                     | –                         |

Data from Meteo sensors were not corrected in the study.
from each sensor type, which were found to effectively reduce the biases by around 80%.

Findings from the study raise several points. Firstly, studies on WegenerNet data under various weather conditions can be informative for the use of data for a specific purpose, for example, for validating other data (e.g., from radar) or model output fields. Further quantitative evaluations on the sub-daily data or on the specific events such as extreme rainfall, light rainfall, and solid precipitation could provide more detailed information on the uncertainties in the data. Secondly, an additional analysis on the whole WegenerNet station network is required to assess uncertainties in the spatial sampling of the data that are of interest, particularly for the use of WegenerNet as a ground validation reference. Lastly, the high spatial resolution of WegenerNet data can be beneficial for addressing research questions that need rainfall data at different scales over the 1-km to 10-km scale range. For example, the sensitivity of small catchment models to rainfall data or the evaluation of rainfall under-sampling during intense convective rainfall events could draw key advantages from WegenerNet datasets.

As a consequence, the results from this study have been reflected in the operation and maintenance of the WegenerNet and in the improvement of the data for user applications. For example, the bias correction factors in this study for the Friedrichs and Young sensors were applied to all rainfall values in the new version (v5) level 2 data. All versions are available at the WegenerNet data portal. Furthermore, we concluded that there was a mechanical problem in the sensor of station W145, which showed strong underestimates, rather than systematic errors, so it has already been replaced. In addition, and as a fundamental long-
term improvement, a major sensor replacement cycle during 2016, after about 10 years of WegenerNet operations, was recently completed by August 2016. We installed the high-quality Meteo sensors also at all 138 base stations in the complete network during this cycle; at these stations without a heating system. At the same time, we keep operating the WegenerNet reference station with all three different sensors for the purpose of continuing sensor intercomparison. We therefore expect that WegenerNet will be a unique high-density precipitation measurement network for the hydro-meteorological communities for many years to come.

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Appendix A. Quality flags and errors in WegenerNet daily precipitation data

This appendix addresses errors in WegenerNet daily precipitation data (2007–2014) for all quality flag levels of the data (see Table 2 for the brief description of quality flags and Kirchengast et al. (2014) for details). Note that the quality flag for daily data is an average of all flags on native resolution (5 min) data. Figs. A.1 and A.2 present bias and RMSE of WegenerNet data compared to the reference stations, respectively (similar to Fig. 6, but for all quality flag levels). The errors were obtained for each month, since Table 2 indicated that the number of quality flags is seasonally dependent; there are more non-zero quality flagged data during winter, which is related to solid precipitation.

The WegenerNet Quality Control System (QCS) assumes that the station measures solid precipitation if the mean measured temperature during the last five hours is lower than 2°C. Then the stations with Friedrichs sensors get spatially interpolated values of the measurement at the 12 heated stations instead of their own measurements. Those data are flagged by a quality flag of 3 (interpolation from grid) or 4 (no interpolation possible, e.g., if some of the heated stations have malfunctions). From May to September, the temperature is mostly above 2°C, so there are always enough unheated stations for direct interpolation (q2 flag). This is why there are no errors from q3 and q4 data during this period, as depicted in the figures.

Generally, Figs. A.1 and A.2 show that q0 data cause the smallest errors for bias and RMSE. Relatively high errors are observed from the q1 data around summer, from May to September, while the high errors for q3 or q4 data are detected during the months from October to April. To illustrate the source of the errors, one case of q1 data in August and one of q4 data in April were further investigated using 10-min data of the WegenerNet and ZAMG stations.

During a short-duration rainfall event in the cluster of Z298 on 2 August 2008, only the W060 station data were flagged by q1, and the rainfall recorded at the station was 6.8 mm d⁻¹, which is much less than other WegenerNet stations (11.5 mm d⁻¹ on average) and the reference (19.1 mm d⁻¹). Raw measurements at W060 were flagged by the QCS for several hours, since the values deviated too much from the values of neighboring stations, probably due

![Fig. A.1. Box-and-whisker plots showing bias of WegenerNet daily precipitation data [mm d⁻¹] compared with their reference stations for each month and quality flag. Data from all 20 WegenerNet stations (red) were used in the plots.](image-url)
to a blocked funnel at the station. Since only raw measurements that passed all QCS checks are used to generate the data, 5-min data at station W60 were generated through spatial interpolation (i.e., flagged by q2), and the daily data, consequently, has a q1 flag from averaging with q0 data during a day.

Another example is a solid precipitation event in cluster Z244 on 2 April 2013. Austria had an unusually cold spring in 2013, and temperatures had been below 2°C for most of the day. As a result, the WegenerNet QCS decided to interpolate data from the heated stations to generate the solid precipitation data, except the result, the WegenerNet QCS decided to interpolate data from the heated stations to generate the solid precipitation data, except for two hours in the afternoon when the temperature rose above 2°C. However, the QCS could not secure enough data for the interpolation due to malfunctions of most heating systems, finally we get only the missing values (q4 flag). This leads to discrepancies in the daily data records between stations (WegenerNet recorded 10.6 mm d⁻¹, while ZAMG recorded 17.5 mm d⁻¹).

In conclusion, it was found that a small amount of data collected under a specific adverse weather conditions can cause unexpectedly high errors in daily data records. Therefore, we minimized those errors by using only q0 rainfall data in this study.

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