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Evaluation of precipitation measurements methods under field conditions during a summer season: a comparison of the standard rain gauge with a weighable lysimeter and a piezoelectric precipitation sensor

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Abstract

Current precipitation measurements are conducted largely by simple automatic rain gauges. Despite being error-prone and sometimes of questionable accuracy, the procedure is still widely used. In recent years new possibilities have emerged, which are based on different measuring principles. Although the application of alternative devices is increasing, its use in research is limited. In this study, precipitation measurements by different devices were compared, and systematic errors caused by individual characteristics were corrected. Data were collected by means of a monitoring network, which included a piezoelectric precipitation sensor mounted at 2.3 m, a standard tipping bucket at 1 m, and a weighable gravitation lysimeter at ground level. As measurements at ground level are considered as optimum, the records of the lysimeter were thereby determined as a reference. The results showed that precipitation measured by elevated rain gauges differed in total between -6.8% and +35% compared to rainfall measured by the lysimeter. The records correlated well, but the analyses indicated a strong influence of the precipitation intensity on the recorded amount of precipitation. The deviations between values of the rain gauges and those of the lysimeter increased with rainfall intensity. In general, the tipping bucket demonstrated negative error values and indicated an underestimation of precipitation compared to records at ground level, whereas the piezoelectric precipitation sensor showed an overestimation by highly positive error values. A subsequent precipitation correction through the linear scaling method improved significantly the raw data of the rain gauges.

***Highlights (3 to 5 bullet points (maximum 85 characters including spaces per bullet point)**

Highlights

- Data availability is limited in Siberia
- Tipping bucket underestimates precipitation compared to rainfall at ground level
- Piezoelectric precipitation sensor overestimates precipitation
- Measurement errors are strongly dependent on rainfall intensity
- Linear scaling method failed at high rainfall intensities

Evaluation of precipitation measurements methods under field conditions during a summer season: a comparison of the standard rain gauge with a weighable lysimeter and a piezoelectric precipitation sensor

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Current precipitation measurements are conducted largely by simple automatic rain gauges. Despite being error-prone and sometimes of questionable accuracy, the procedure is still widely used. In recent years new possibilities have emerged, which are based on different measuring principles. Although the application of alternative devices is increasing, its use in research is limited. In this study, precipitation measurements by different devices were compared, and systematic errors caused by individual characteristics were corrected. Data were collected by means of a monitoring network, which included a piezoelectric precipitation sensor mounted at 2.3 m, a standard tipping bucket at 1 m, and a weighable gravitation lysimeter at ground level. As measurements at ground level are considered as optimum, the records of the lysimeter were thereby determined as a reference. The results showed that precipitation measured by elevated rain gauges differed in total between -6.8% and +35% compared to rainfall measured by the lysimeter. The records correlated well, but the analyses indicated a strong influence of the precipitation intensity on the recorded amount of precipitation. The deviations between values of the rain gauges and those of the lysimeter increased with rainfall intensity. In general, the tipping bucket demonstrated negative error values and indicated an underestimation of precipitation compared to records at ground level, whereas the piezoelectric precipitation sensor showed an overestimation by highly positive error values. A subsequent precipitation correction through the linear scaling method improved significantly the raw data of the rain gauges.

Keywords: precipitation; precipitation correction; bias; tipping bucket rain gauge; lysimeter; piezoelectric precipitation sensor

1 Introduction

Quantification of precipitation is important for many reasons. Information about rainfall, obtained from accurate point measurements, is widely used in climatology, hydrology or agrometeorology. However, this method of precipitation measurement is associated with systematic underestimation (Sevruk, 1982; Richter, 1995; Førland et al., 1996; Goodison et al., 1998), which may strongly impair the accuracy. The effects of systematic errors on the quality of measurements depend on gauge design and their installation specifics, the surrounding area, meteorological parameters, and type of precipitation (Sevruk, 1982; Legates and DeLiberty, 1993). The well-known error sources, particularly caused by wind, wetting and evaporation loss, have affected all types of rain gauges for a long time. Especially, the installation of rain gauges at heights between 0.5 and 1.5 m above ground level (World Meteorological Organization, WMO, 2014) often result in erroneous recorded values up to 75% of single precipitation events (Neff, 1978).

According to WMO, there are three types of automatic precipitation recorders, which are deemed to be standard rain gauges: the weighing-recording type, the tipping bucket type, and the float type. All these devices are susceptible to error sources as mentioned above (WMO, 2014). Meanwhile, there are other new automatic recording gauges that are based on the optical or acoustical detection. Despite the advances, precipitation measurements at ground level are optimal, because the conditions are identical to the surrounding area and the wind-induced error is negligible (Mekonnen et al., 2015). Furthermore, measurements at ground level are the true reference since they show more precipitation than any elevated rain gauge (WMO, 2014).

Lysimetry is originally a method for the investigation of soil hydrology and soil chemistry. In the last few years, however, lysimeters will be increasingly used for precipitation measurements due to the high precision weighing system (von Unold and Fank, 2008;

Meissner et al., 2010; Schrader et al., 2013; Peters et al., 2014; Gebler et al., 2015; Herbrich and Gerke, 2016; Hoffmann et al., 2016). The advantage of lysimeters in rainfall recording lies in the recognition that they do not exhibit the commonly occurring errors associated with the standard rain gauges. However, vibrations caused by wind, maintenance, and fieldwork or due to animals entering the lysimeter vessel are sources of errors.

In this study, a monitoring network enables comparable analyses of precipitation measurements by three different types of rain gauges. These are an automatic tipping bucket, which corresponds to the standard device according to the WMO, a weighable gravitation lysimeter whose mass changes provide an estimation of precipitation, and a piezoelectric precipitation sensor, which is based on acoustic detection of raindrop impacts. All devices were part of the monitoring network that was developed in the framework of the research project KULUNDA (Balikyn et al., 2016) in south-western Siberia.

The main objective of this paper is to evaluate precipitation measurements of rain gauges in comparison with lysimeter data at ground level. Based on the results, this study also applies a bias correction method to decrease systematic errors such as, in this case, different gauge designs.

2 Material and methods

2.1 Site description

The study area is part of the south-west Siberian Kulunda steppe lowland and located between the Central Asian steppe and the North Asian forest-steppe (Balikyn et al., 2016). North of Kulunda steppe is the Baraba forest steppe, and the eastern part of the Irtysh valley in Kazakhstan is situated in the west. The site is located at altitudes of 100-140 m a.s.l. and it is covered by a 50 to 60 cm thick layer of Pleistocene alluvial and 0.5-10 m of eolian sediments. Typical soils of the area are chestnut, meadow–chestnut, meadow, solonetz, and solonchak.

The Kulunda steppe is characterised by a continental climate with long, cold and little snowy winters and short, hot and dry summers (Meissner et al., 2017). The steppe is often affected by cold air masses from the Kara Sea and warm and dry ones from Kazakh and Middle Asian steppes and deserts. Thus, dry winds are common and the temperatures are highly variable throughout the year. In spring, very dry periods are characteristic. Usually, night frost occurs in May and September. In late snow-free autumn periods, the temperature drops down to -20 °C or lower. The mean annual temperature is about 0 °C, the absolute minimum -47 °C, and the absolute maximum +40 °C. The mean temperature of the coldest month (January) is -19 °C, whereas the warmest month (July) has a mean temperature of +19 °C. The frostless period lasts between 112 to 120 days per year from late May to early September. The annual precipitation is about 250-450 mm. From April to October, the precipitation is about 200 mm. From November to April a constant snow cover lasts for a period of 140-150 days with a mean depth of 15 cm (absolute maximum 35-38 cm). Furthermore, in winter, the soils freeze down to 2 m deep (and even more). The global radiation is 2-3 times higher than the energy that is required to evaporate the precipitation.

2.2 The monitoring network

The monitoring network consisted of a weather station and a weighable gravitation lysimeter station (Fig. 1) (Meissner et al., 2017). The weather station was established in September 2012 and included a multisensor at a height of 2.3 m (recording wind speed, wind direction, air temperature, air humidity, barometric pressure, rainfall), a pyranometer at a height of 2 m (recording solar radiation), and a tipping bucket rain gauge at the standard height of 1 meter (recording liquid and solid precipitation).

The first precipitation measuring device used in this study was the precipitation sensor of the multisensor (Weather Transmitter WXT520; manufacturer “Vaisala Inc.”, Finland). It consisted of a steel cover and a piezoelectric sensor (Vaisala, 2012), capable of detecting individual raindrops, which are subsequently converted to cumulative rainfall. This is possible since the signal strength is proportional to the volume of all the drops. Interferences originating from other sources were filtered by using advanced noise filtering techniques. Further information about precipitation properties is given in Table 1, whereby the piezoelectric precipitation sensor will be denoted hereafter as “Prec. Sensor”.

The tipping bucket rain gauge (manufacturer “ecoTech”, Germany), which was also used in the study was based on the “Guide to Meteorological Instruments No. 8” (WMO, 2008). The instrument was appropriate to measure the amount of rainfall and rainfall intensity (Thies Clima, 2008). A receiving surface of 200 cm^2 collected the rain, which was conducted through an inflow-sieve into a tipping bucket. An amount of 2 cm^3 led tipped the bucket that was equivalent to 0.1 mm precipitation. This tipping procedure produced an electrical signal which was recorded by a data logger. Since the number of tipping was not linearly related to the precipitation intensity, an intensity-dependent linearisation was carried out by a data logger, based on an intensity-dependent pulse-number-correction for the precipitation intensity range of approximately 0.5 to 11 mm/min.

During June-August 2013 a containerised (Polyethylene PE-HD) lysimeter station with two weighable soil monoliths (manufacturer “UGT-Muencheberg”, Germany and Helmholtz Centre for Environmental Research – UFZ, Germany) was installed at the test farm of the KULUNDA-project in Poluyamki (N52° 03.959’ E79° 42.786’; approximately 700 km south-west of Novosibirsk) (Balikyn et al., 2016). The soil monoliths were monolithically extracted from an arable land and from a fallow site, which was covered with natural steppe vegetation since the 1950s. The lysimeters had a surface area of 1 m^2 and a depth of 2 m. A detailed description of the lysimeters is given by Meissner et al. (2017). The soils were identified as Calcic Chernozems according to the FAO guidelines. The vessels were positioned into the lysimeter station on load cells by using a three-legged steel frame (Meissner et al., 2007). The lysimeter mass was measured with a high precision of ± 20 g (Xiao et al., 2009). The total mass of each lysimeter vessel was approximately 4000 kg and the mass changed by water input (precipitation, dew, rime and the water equivalent of snow) and water output (actual evapotranspiration). Both lysimeters were equipped with frequency-domain reflectometry (FDR) probes for the measurements of the soil moisture and the soil temperature, watermark-sensors for matrix potential measurements, and suction cups to extract soil solution. All sensors were installed at depths of 30, 50, and 120 cm, respectively. The amount of seepage water was collected in a storage container upon measuring by tipping bucket. The surface runoff was measured by a fixed drain at the container wall, which channelled the water to an additional tipping bucket.

All data were consolidated and stored in the respective data logger with a recording interval of one hour (Tab. 1).

Figure 1

Table 1

2.3 Data availability

To compare precipitation measured by the different systems identical time series were required. Due to the different time of installation synchronous measurements were only available from August 2013 to September 2016. The major challenge of precipitation measurements by lysimeters was the malfunction during winter in Siberia. Sub-zero temperatures and snow led to an inexplicable increase of the lysimeter mass. The failure-free operation was restarted in spring. Rising temperatures and frostless nights were necessary to stabilise the system at the initial time periods. Therefore, all periods between October and May were non-applicable for data analysis. Sufficient data were available during summer. The longest time series without data gaps was between 9th June and 30th September 2016 which was appropriated as investigation period. The two lysimeters were originally used for reference analyses between arable land and unconverted grassland. Thus, there was an ascertained crop rotation at the arable lysimeter: wheat (2013), peas (2014), wheat (2015), and fallow (2016). In contrast, the pristine lysimeter was dominated by natural feather grass (Stípa pennáta) between 2013 and 2016. Considering the purpose of the study only the data of the arable lysimeter in 2016 are suitable for an unrestricted comparability to the rain gauges. The absence of vegetation represents the ideal condition to measure precipitation at ground level because there are no external factors that have a direct effect on the measurements. Although the development of ruderal vegetation was observed, the percentage of the canopy was still small during the investigated period so that the interception of vegetation, which is part of the precipitation term, is negligible.

2.4 Data preparation

The processing of precipitation data of Prec. Sensor and tipping bucket rain gauge was followed the same procedure. First, the cumulative data were converted into absolute values per hour. In step two, the raw data was manually filtered, and all data during system error or noticeable outliers was removed. When the resulting gaps did not exceed a period of four hours, the values were estimated by linear interpolation. The processing of lysimeter data was done according to the principle of the adaptive window and adaptive threshold filter (AWAT), developed by Peters et al. (2014). The AWAT filter is an approach to filter and smooth noisy lysimeter data.

2.5 Calculating precipitation from lysimeter data

Meissner et al. (2000, 2007, 2010) have shown that weighable lysimeters were able to measure water fluxes with high precision. The total mass of the system (M) was the sum of the mass of lysimeter (M_{lys}) and of drainage (M_{drain}). It is assumed that a mass increase corresponds to precipitation (P) and a mass decrease was actual evapotranspiration (ET_a). With this assumption, P and ET_a cannot take place within the same time interval. ET_a is equal to zero when P occurs, and vice versa. Therefore, P was calculated from the mass changes of lysimeter by Schrader et al. (2013):

$$M = M_{lys} + M_{drain}$$

$$P = \begin{cases} \Delta M & for \quad \Delta M > 0 \\ 0 & for \quad \Delta M \leq 0 \end{cases} \quad (1)$$

$$ET_a = \begin{cases} \Delta M & for \quad \Delta M < 0 \\ 0 & for \quad \Delta M \geq 0 \end{cases}$$

In Eq. (1), M_{lys} [kg] is the mass of lysimeter vessel, M_{drain} [kg] is the amount of seepage water, and ΔM [kg] is the total mass change of lysimeter vessel in the according time interval. Due to the geometry of the lysimeter vessel mentioned above, a change of mass is equal to a water storage change in millimeters (1 kg ≈ 1 l/m² = 1 mm). Therefore, all changes of mass are given in millimeters henceforward.

2.6 Data analyses

After data have been converted to hourly P values the study considered only rainfall data at least one measurement station. Time steps without rainfall at all three stations and data lower than 0.1 mm $hour^{-1}$ were removed. The latter is justified by the output resolution of the tipping bucket. Furthermore, the impact of dewfall at the lysimeter which may misinterpret as P is thereby avoided. Depending on the aims of data use, P can be expressed at different time scales. Where daily values are required, the hourly values are summed-up for one day, starting from 0.00 UTC and follows to 24 hours.

The evaluation of data is carried out by means of statistical indices. The correlation of Pearson (r), bias (Eq. 2), relative bias (rbias, Eq. 3), mean absolute error (MAE, Eq. 4), and the root mean squared error (RMSE, Eq. 5) were calculated. Let the variables X_i and Y_i be the *i*th value from the particular rain gauge and the lysimeter, respectively.

$$\text{bias} = \sum_{i=1}^{N}(X_i - Y_i)/N \tag{2}$$

$$\text{rbias} = \left(\sum_{i=1}^{N}(X_i - Y_i)/\sum_{i=1}^{N}Y_i\right) \times 100 \tag{3}$$

$$\text{MAE} = \frac{\sum_{i=1}^{N}|X_i - Y_i|}{N} \tag{4}$$

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^{N}(X_i - Y_i)^2}{N}} \tag{5}$$

The error indices indicate how well the data of the rain gauges agree with the observed data of the lysimeter. Positive bias and rbias indicate an overestimation and negative values show an underestimation, while MAE and RMSE values of 0.0 show a perfect match between the measurements.

In order to correct bias in the rain gauge data and defining correction factors the linear scaling of P was conducted. The method aims to decrease the bias between observed and raw data by calculating monthly correction factors on a daily basis and multiplying them with the raw value (Fang et al., 2015):

$$P_{cor,m,d} = P_{raw,m,d} \times \frac{\mu\,(P_{obs,m})}{\mu\,(P_{raw,m})}, \tag{6}$$

where $P_{cor,m,d}$ is the corrected P on the *d*th day of the *m*th month, $P_{raw,m,d}$ is the raw P on the *d*th day of the *m*th month, and μ is the mean value of observed and raw P at given month *m*. The observed and raw P corresponds to the lysimeter and the rain gauges, respectively.

3 Results and discussion

3.1 Comparison of P measurements

The cumulative P of the lysimeter (LYS), Prec. Sensor and tipping bucket (TB) was compared during 44 days of rainfall (Fig. 2). Most of P was recorded by Prec. Sensor with a total of 229.4 mm, whereas TB measured the lowest sum of 158.4 mm. Values of LYS with a sum of 169.9 mm ranged between Prec. Sensor and TB. The cumulative P from rain gauges showed relative differences ranging from +35% (Prec. Sensor) to -6.8% (TB) in comparison to LYS.

Results of the monthly analysis are given in Table 2. In a month by month comparison, the maximum and minimum of P were measured by Prec. Sensor and by TB, except for September where LYS presented the lowest P value. The smallest relative deviations were between LYS and TB which varied in -5.5% and -5.8% in June and August, whereas the deviations with -8.9% and +33.3% were increased in July and September, respectively. In contrast, P records of Prec. Sensor are totally unconnected with those by LYS because a continuous increase in deviations (up to +88.3% in September) was stated.

Figure 2

Table 2

Daily precipitation measurements correlated well with those of the rain gauges with r varying between 0.87 and 0.91 (Fig. 3). Daily P values of LYS, TB and Prec. Sensor ranged from 0 to 16.4 mm day^{-1}, from 0 to 23.7 mm day^{-1}, and from 0 to 25.1 mm day^{-1}, respectively (Fig. 4). Data of Prec. Sensor showed a median of 2.2 mm day^{-1} and they covered the widest range of values, whereas P measured by TB yielded the lowest values and a median of 0.8 mm day^{-1}. Usually, P rate decreased with increasing measuring height (Sevruk, 1981; Fank and Klammler, 2013; Gebler et al., 2015; Hoffmann et al., 2016). Therefore, the installation height of TB justified the lower P rates compared to those measured at ground level. In addition, the smaller receiving surface, wind-field deformation, evaporation, splashing or wetting loss at the internal wall of the collector may also have reduced the measuring results. On the other hand, Prec. Sensor should show lower values than TB and LYS due to the measuring height of 2.3 m. According to the manufacturer, Prec. Sensor has to measure up to 30% less P than rain gauges at ground level (Vaisala, 2012). The disagreement cannot be explained without additional investigations. It is not due to systematic measurement errors of standard rain gauges. The measuring principle is based on the detection of individual raindrop impacts. Therefore, variation in the shape and velocity of raindrops caused by air movements was the major error factor. A further malfunction source could be the sensitivity variations over the sensor area due to surface wetness (Salmi and Ikonen, 2005).

Figure 3

Figure 4

According to the German Meteorological Service (Deutscher Wetterdienst - DWD) rainfall intensity can be classified as light rain (<2.5 mm hour^{-1}), moderate rain (2.5-10 mm hour^{-1}) and heavy rain (>10 mm hour^{-1}). Within the studied time period, the absolute frequency of occurrence (i.e., the number of rainfall events that occur under a certain condition) decreased with increased rainfall intensity. Precipitation with light intensity predominated with a contribution of 78 to 88% to the total rainfall (Fig. 5). LYS demonstrated a higher frequency of light rainfall than the rain gauges, but the absolute frequency of Prec. Sensor exceeded TB and LYS at moderate rainfall. Overall, moderate rainfall occurred with an absolute frequency of <21 and a percentage of 11% in the rain gauges. Events with rainfall intensity >10 mm hour^{-1} did not occur at LYS, but it was measured twice at TB and four times at Prec. Sensor which accounted for a share of around 3%.

It has been observed that the differences in P between LYS and rain gauges are dependent on rainfall intensity. The higher the rainfall intensity the larger the errors to P measured by LYS became (Tab. 3). Prec. Sensor, as well as TB, demonstrated mostly similar differences. At light rainfall, they showed error values up to 2.9 mm hour^{-1}. When LYS recorded moderate rainfall MAE and RMSE increased to approximately 4 mm hour^{-1}. As LYS have measured no heavy rainfall, the calculation of MAE and RMSE based on the rainfall events >10 mm recorded by Prec. Sensor. It should be mentioned that in the case of light or moderate rainfall detected by LYS and a simultaneous heavy rainfall detected by the rain gauges, the rainfall at the rain gauges should be regarded as an error of light or moderate rainfall. Nevertheless, MAE and RMSE have reached a maximum of 14.9 mm $hour^{-1}$ and 16.2 mm $hour^{-1}$, respectively.

These significant deviations could possibly demonstrate an overestimation of P by Prec. Sensor due to the high velocity of raindrops. This assumption may be confirmed by the more frequent measurements of P which were classified as moderate and heavy rainfall. However, on 9^{th} July 2016, a phenomenon was observed which could be the reason for higher differences. The rain gauges measured up to 52% more P than LYS. If high P amount falls in a short time, water runs off across the LYS collar because the infiltration capacity of the previous dried-up soil becomes exceeded. This water was not recorded as P but rather as surface runoff. The lysimeter recorded a daily surface runoff of 4.3 mm. If this amount will be assumed as P, the deviation to P measured by the rain gauges becomes lower up to 30%.

Figure 5

Table 3

3.2 Bias correction

There are several reasons for the correction of rainfall data. Usually, it will be used for model calibration and validation since the simulations are often far different from observations. On the other hand, rainfall data can also be obtained from novel gauges or remote sensing which show other systematic errors and uncertainties. As rainfall data may vary considerably in their accuracy due to different measuring principles, data correction is necessary to decrease bias between the measurement devices. For this purpose, there are a lot of methods to correct bias (Teutschbein & Seibert, 2012; Fang et. al., 2015, Sungmin et al., 2018). In this study, the linear scaling method was chosen due to the exclusive use of wet days ($P > 0.1$ mm) and derivation of correction factors. According to Eq. 6, correction factors and results are shown in Table 4 and Figure 6. The method significantly improved the raw data of the rain gauges. However, there were remained mismatches between LYS and corrected data where the rain gauges, for instance, did not follow the temporal pattern of LYS. This state of affairs was the result of the fact that the temporal record of devices occasionally differed. Precipitation rates were cumulated and were provided as an absolute value at rain gauges, whereas LYS sometimes recorded the same rate distributed over hours. Thus, LYS showed a delayed response to rainfall. This phenomenon was noticeable during the analysis of daily P rates. This was peculiar with night rainfall. The amount of rainfall measured by rain gauges was summed-up for one day. Due to the delayed record of LYS, the P amount was distributed over two days. Therefore, the daily P rates were lower or higher compared to measurements by rain gauges for the respective day.

Table 5 presents bias, rbias, MAE, and RMSE before and after the correction. The raw data of Prec. Sensor and TB had a total bias of 1.3 mm day^{-1} and -0.3 mm day^{-1}, respectively. Bias and rbias of TB are negative, except for September. MAE and RMSE indicate relatively large total values with 2 and 3.4 mm day^{-1} for Prec. Sensor as well as 1 and 2.1 mm day^{-1} for TB, respectively. These values can result from convective P which is accompanied by high rainfall intensity. Convective systems occur usually during summer. In the investigated period heavy rainfall was particularly measured in July, which led to higher MAE and RMSE. After the correction, the monthly rbias range from 0.01 to -0.09%. MAE and RMSE of Prec. Sensor decreased by 40 and 33%, whereas the error values of TB increased by 1 and 9%, respectively. In general, the corrected data are in good agreement with observed P measured by LYS. Shrestha et al. (2017) have proved that the linear scaling method delivers good results despite the simple technique. Recent studies are strongly in favour of the superiority of complex bias correction methods, but the simple implementation and similar performance compared to complex methods are arguments for their application. The big drawback is, however, the inability to correct the rainfall intensity as it could be observed in the data of July. The approach overcorrected rbias, MAE, and RMSE of TB and underestimated those of Prec. Sensor. Similar results were also found by Fang et al. (2015).

In order to correct rainfall intensity, an alternative technique such as quantile mapping is more appropriate because it modifies the P distribution in expectation of changes due to more frequent extreme rainfall events.

Table 4

Figure 6

Table 5

4 Conclusions

This study compared rainfall data of rain gauges with lysimeter data, and reduced effects of systematic errors resulting from their individual characteristics by P correction. As rainfall measured at ground level is the true reference, it can be assumed that the detection of rainfall by LYS provides precise and reliable rainfall data. However, the inability to account correctly for the effects of surface runoff at high rainfall intensity can lead to an underestimation of P. Furthermore, big drawbacks of the lysimetry and their use in P measurement are the high costs and effort for maintenance. In contrast, P measurements by rain gauges are convenient and inexpensive. Though, this study demonstrated the reduced accuracy compared to measurements at ground level. The application of TB is widely distributed for standard measurements, but TB underestimated significantly the amount of P due to the elevated installation. The application of Prec. Sensor as a new rain gauge is effective due to the maintenance-free and multi-disciplinary ability, but contrary to the statement made by the manufacturer, Prec. Sensor underestimate P up to 30% compared to ground level, the measuring results indicated an overestimation of P. It seems that the shape and velocity of raindrops have some influence on P detection.

Based on different conditions in measuring principle, a bias correction in the data of TB and Prec. Sensor was necessary. There are several P correction methods whose application is case dependent. The aim was to adjust the rain gauges data to the LYS data at ground level.

Therefore, the linear scaling method was an appropriate approach to define correction values which will finally be applied to the raw data. After correction, TB and Prec. Sensor delivered improved rainfall data with decreased error values. Nevertheless, the method has failed for periods with high rainfall intensity. Raw data of TB were overcorrected, whereas the values of Prec. Sensor were underestimated.

Finally, it is not proven whether the calibration of Prec. Sensor is appropriate to other climate zones. Rainfall intensity, raindrop size, shape and rate of fall differ at the regional level, and they potentially require different calibrations. Due to the lack of scientific studies of piezoelectric precipitation sensors, further investigations are necessary, particularly with regard to their calibration and accuracy under different rainfall conditions.

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Figure captions

Fig. 1. Experimental set-up of the monitoring network consisting of multisensor “Vaisala”, tipping bucket rain gauge and two weighable gravitation lysimeters (according to Meissner et al., 2017; modified).

Fig. 2. Cumulative precipitation (P) of Prec. Sensor, the tipping bucket rain gauge (TB) and the lysimeter (LYS) from 09/06/2016 to 31/09/2016.

Fig. 3. The relationship between the rainfall data obtained by the rain gauges and lysimeter (LYS) on a daily basis, respectively, and the Pearson correlation coefficient (r).

Fig. 4. Comparison of rainfall data measured by the lysimeter (LYS), the tipping bucket (TB), and Prec. Sensor. The box plots are based on daily data. The box boundaries represent the 25th and 75th percentiles, the inner lines indicate the medians, the whiskers extend to 1.5 times the interquartile range, the crosses mark the 1st and 99th percentiles, and the strokes show the minimum and maximum values.

Fig. 5. Frequency distribution of daily precipitation rates in different intensity ranges and their contribution to the total rainfall. The vertical bars are related to the left axis; the symbols and lines are related to the right axis.

Fig. 6. The daily precipitation (P) of the lysimeter (LYS) compared to the raw and corrected rainfall of the tipping bucket (TB) and Prec. Sensor.

Figure 1
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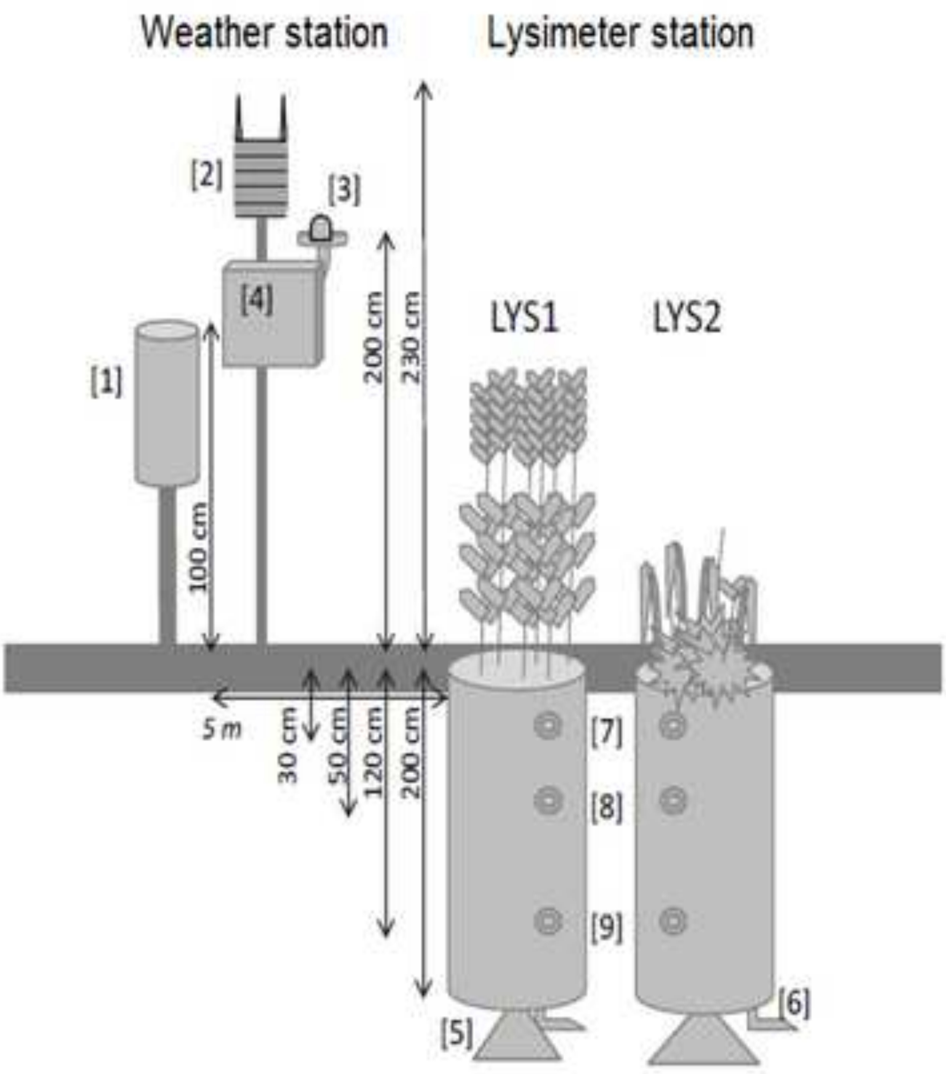

[1]	Tipping bucket rain gauge	[5]	Weighing system
[2]	Multisensor "Vaisala"	[6]	Drainage
[3]	Pyranometer	[7, 8, 9]	FDR, tensiometer, suction cups (30, 50, 120 cm)
[4]	Data logger		

Figure 2
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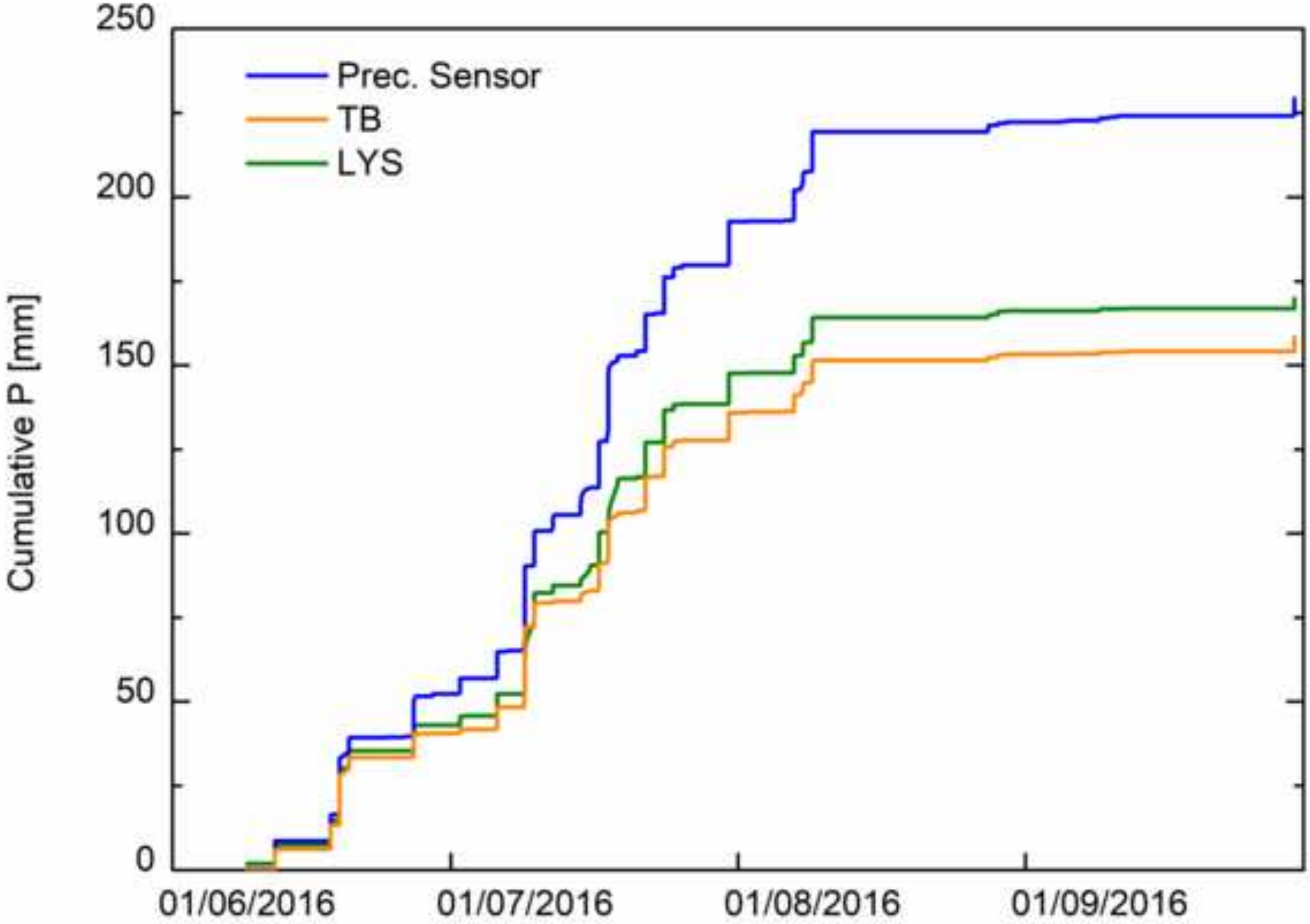

Figure 3

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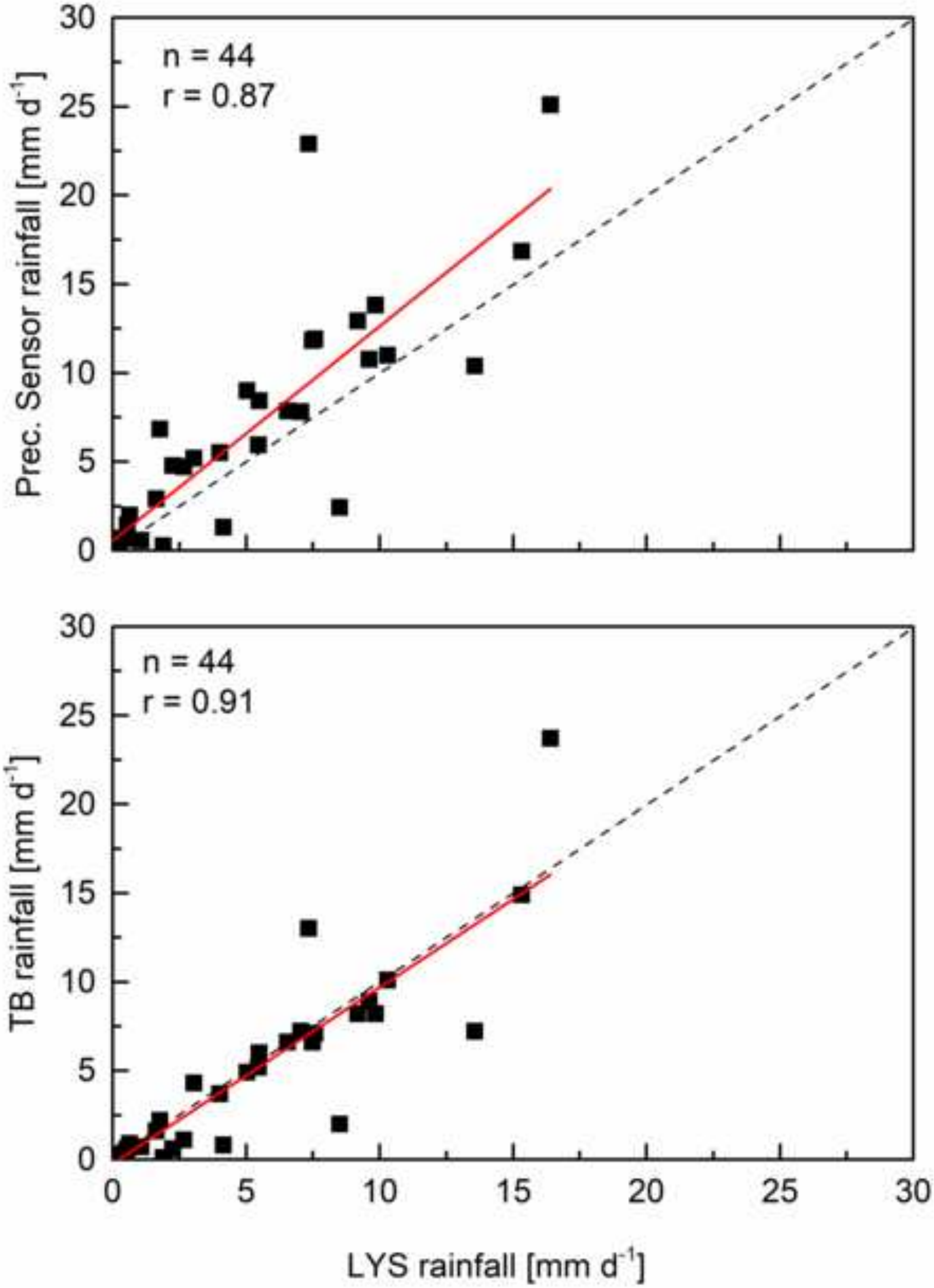

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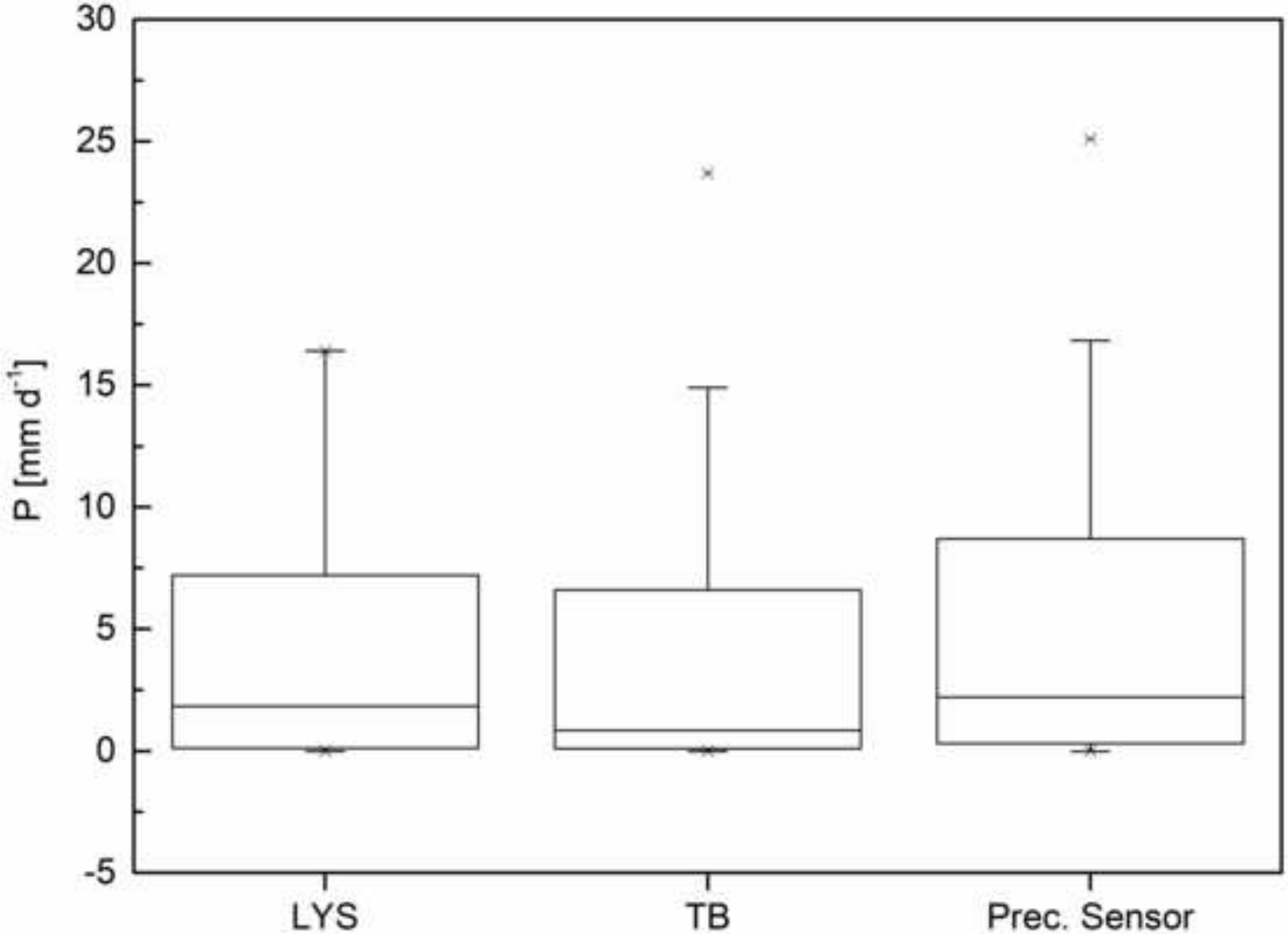

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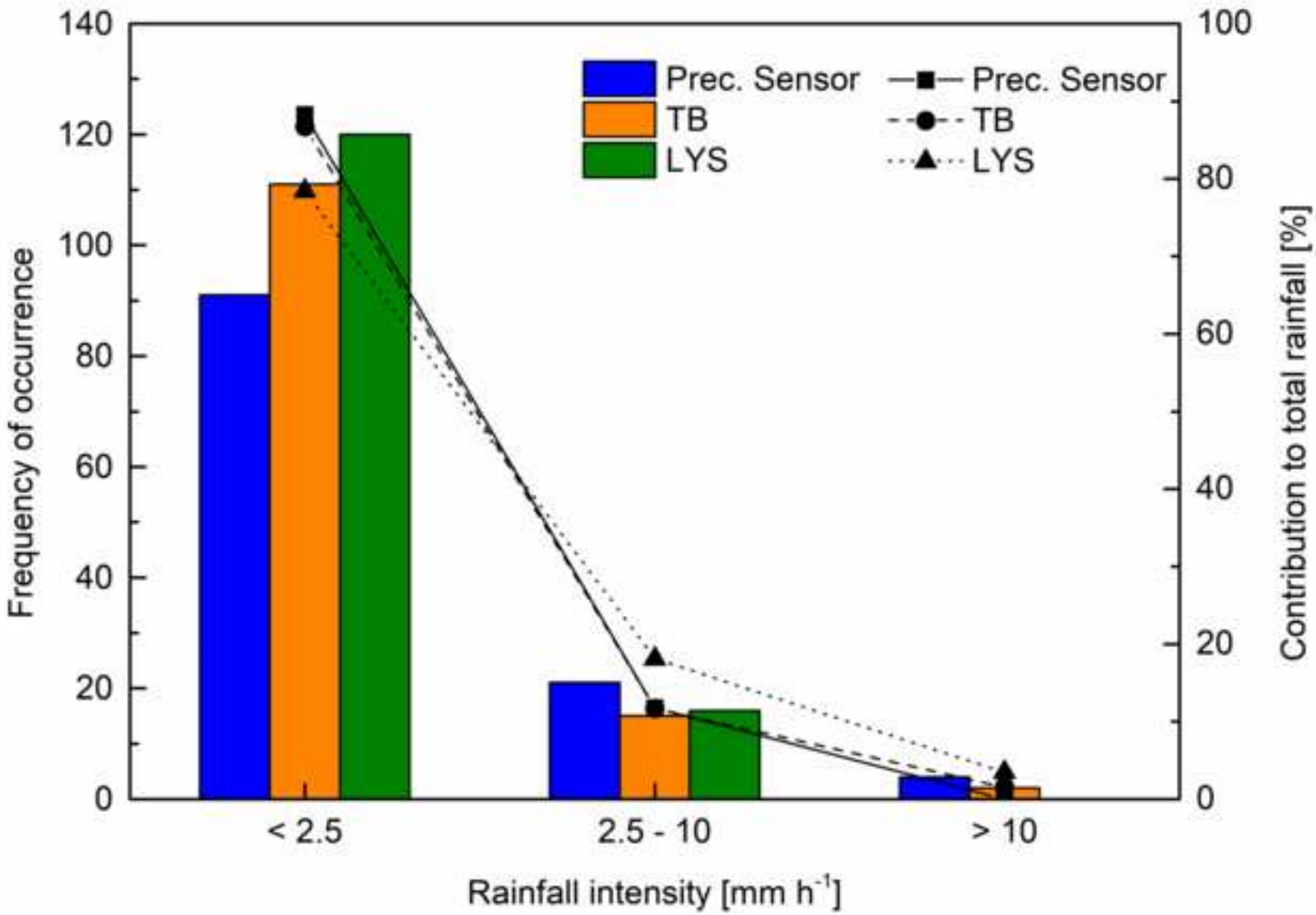

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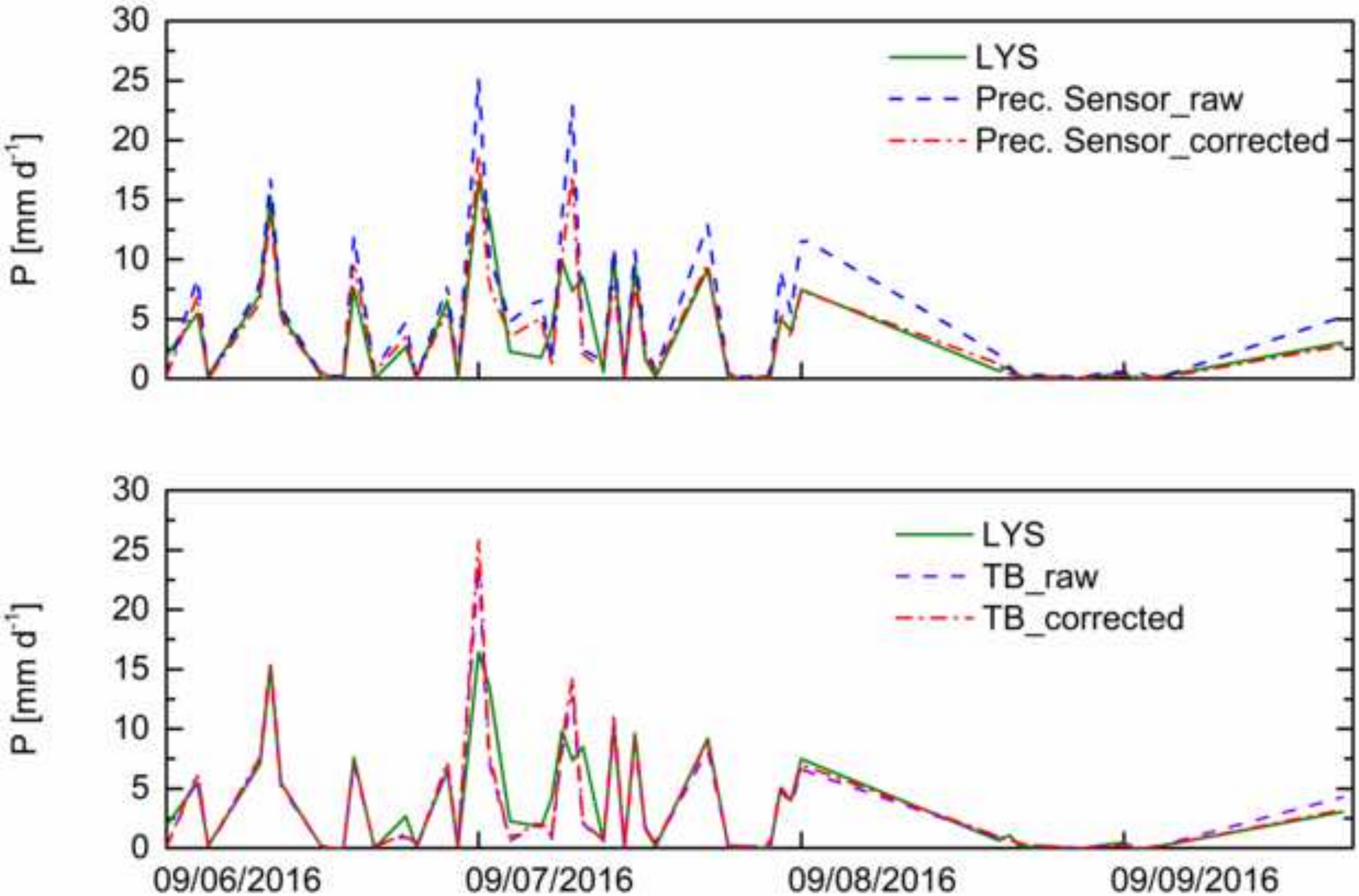

Table 1
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Table 1.
Properties of precipitation measurements by Prec. Sensor, tipping bucket rain gauge and lysimeter

Property	**Prec. Sensor**	**Tipping bucket**	**Lysimeter**
Rainfall	cumulative accumulation after the latest auto or manual reset		
Measuring height (above ground level)	2.3 m	1.0 m	0.0 m
Temporal resolution	60 min	60 min	60 min
Collecting area	60 cm^2	200 cm^2	10 000 cm^2
Output resolution	0.01 mm	0.1 mm	0.02 mm
Accuracy	± 5 %	± 3 %	± 0.0005 %
Measuring range	0 … 200 mm/h	0.5 … 11 mm/min	
Notice	No information regarding calibration	Calibrated with a precipitation of 10 mm	

Table 2

Table 2.
Monthly precipitation (P) of the lysimeter (LYS) and rain gauges

Period	**Number of observation days (n)**	**P**		
		Prec. Sensor	**TB**	**LYS**
Jun	22	52.3	40.7	43.1
Jul	31	140.4	95.3	104.6
Aug	31	29.6	17.4	18.5
Sep	30	7.1	5.0	3.7

Table 3
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Table 3.
The error indices MAE and RMSE as a function of rainfall intensity;
Note that the heavy rainfall events are based on P values of Prec. Sensor

rainfall intensity	MAE		RMSE	
	Prec. Sensor [mm h^{-1}]	TB [mm h^{-1}]	Prec. Sensor [mm h^{-1}]	TB [mm h^{-1}]
light	1.2	0.9	2.9	2.1
moderate	3.7	3.8	4.1	4.2
heavy	14.9	9.9	16.2	12.3

Table 4.
Monthly correction factors for Prec. Sensor and tipping bucket (TB) to reduce bias in the raw data

Month	Prec. Sensor	TB
Jun	0.82	1.06
Jul	0.75	1.10
Aug	0.62	1.06
Sep	0.53	0.75

Table 5
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Table 5.
Comparison of the error indices for Prec. Sensor and tipping bucket (TB) before and after bias correction

		bias		rbias		MAE		RMSE	
		Prec. Sensor [mm d^{-1}]	TB [mm d^{-1}]	Prec. Sensor [%]	TB [%]	Prec. Sensor [mm d^{-1}]	TB [mm d^{-1}]	Prec. Sensor [mm d^{-1}]	TB [mm d^{-1}]
Jun	before	0.9	-0.2	21.5	-5.5	1.3	0.4	1.8	0.6
	after	0.0	0.0	0.0	0.0	0.9	0.4	1.1	0.6
Jul	before	1.9	-0.5	34.2	-8.9	3.2	1.9	4.8	3.1
	after	0.0	0.0	-0.01	0.01	2.1	2.0	3.3	3.5
Aug	before	1.4	-0.1	60.5	-5.8	1.5	0.3	2.2	0.4
	after	0.0	0.0	-0.03	-0.03	0.3	0.2	0.4	0.2
Sep	before	0.5	0.2	88.3	33.3	0.5	0.2	0.8	0.5
	after	0.0	0.0	-0.08	-0.09	0.1	0.1	0.2	0.1