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RAIN GAUGE INTER-COMPARISON QUANTIFIES DIFFERENCES IN PRECIPITATION MONITORING

COMPARACIÓN ENTRE PLUVIÓMETROS CUANTIFICA DIFERENCIAS EN EL MONITOREO DE LA PRECIPITACIÓN

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Resumen

Por décadas se ha trabajado para corregir las medidas de precipitación, sin embargo estos esfuerzos han sido escasos en zonas tropicales montañosas. Cuatro pluviómetros de balancín (TB), con distinta resolución y comúnmente utilizados en las montañas de los Andes, fueron comparados en este estudio: un DAVIS-RC-II, un HOBO-RG3-M, y dos TE525MM (con y sin una pantalla Alter contra el viento). El desempeño de estos pluviómetros, instalados en el Observatorio Ecohidrológico Zhurucay, sur del Ecuador, a 3780 m s.n.m., fue evaluado en relación al sensor de mejor resolución (0,1 *mm*), el TE525MM. El efecto de la intensidad de precipitación y condiciones del viento también fue analizado utilizando 2 años de datos. Los resultados revelan que (i) la precipitación medida por el TB de referencia es 5,6 % y 7,2 % mayor que la de pluviómetros con resolución de 0,2 *mm* y 0.254 *mm*, respectivamente; (ii) la subestimación de los sensores de menor resolución es mayor durante eventos de baja intensidad—una máxima diferencia de 11 % para intensidades $\leq 1\ mm\ h^{-1}$; (iii) intensidades menores a $2\ mm\ h^{-1}$, que ocurren el 75 % del tiempo, no pueden ser determinadas con exactitud para escalas menores a 30 minutos debido a la resolución de los pluviómetros, e.g. sesgo absoluto $> 10\%$; y (iv) el viento tiene un efecto similar en todos los sensores. Este análisis contribuye a mejorar la exactitud y homogeneidad de las medidas de precipitación en los Andes mediante la cuantificación del rol clave de la resolución de los pluviómetros.

Palabras clave: Pluviómetros de balancín, análisis comparativo, exactitud de medición, efectos de intensidad y viento, tropical.

Abstract

Efforts to correct precipitation measurements have been ongoing for decades, but are scarce for tropical highlands. Four tipping-bucket (TB) rain gauges with different resolution that are commonly used in the Andean mountain region were compared-one DAVIS-RC-II, one HOBO-RG3-M, and two TE525MM TB gauges (with and without an Alter-Type wind screen). The relative performance of these rain gauges, installed side-by-side in the Zhurucay Ecohydrological Observatory, south Ecuador, at 3780 m a.s.l., was assessed using the TB with the highest resolution (0.1 *mm*) as reference, i.e. the TE525MM. The effect of rain intensity and wind conditions on gauge performance was estimated as well. Using 2 years of data, results reveal that (i) the precipitation amount for the reference TB is on average 5.6 to 7.2% higher than the rain gauges having a resolution of 0.2 *mm* and 0.254 *mm* respectively; (ii) relative underestimation of precipitation from the gauges with coarser resolution is higher during low-intensity rainfall mounting to a maximum deviation of 11% was observed for rain intensities ≤ 1 $mm\ h^{-1}$; (iii) precipitation intensities of 2 $mm\ h^{-1}$ or less that occur 75% of the time cannot be determined accurately for timescales shorter than 30 minutes because of the gauges' resolution, e.g. the absolute bias is >10%; and (iv) wind has a similar effect on all sensors. This analysis contributes to increase the accuracy and homogeneity of precipitation measurements throughout the Andean highlands, by quantifying the key role of rain-gauge resolution.

Keywords: Tipping-bucket rain gauge; comparative analysis; measurement accuracy; intensity and wind effect; tropical.

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1 Introduction

Hydrological studies require precipitation as input (Vuerich et al., 2009; Savina et al., 2012; Seo et al., 2015; Muñoz et al., 2016) and in response to this several rainfall sensors, featuring different operational and technological principles, have been developed. Among point-based recording sensors the tipping bucket, weighing and floating gauges are the most widely used (Nystuen, 1999; WMO, 2008; Grimaldi et al., 2015). In particular, the tipping bucket (TB) gauge is a very popular device, used all over the globe (Humphrey et al., 1997; Habib et al., 2001; Tokay et al., 2003; Molini et al., 2005; Vuerich et al., 2009; Mekonnen et al., 2014; Chen and Chandrasekar, 2015; Dai, 2015; Keller et al., 2015). TBs are in general low-cost, but depending on the manufacturer can have different resolution and accuracy for measuring rainfall. According to Savina et al. (2012) inaccuracies in measurements of TB gauges are primarily due to the precipitation variability and sensitivity to environmental conditions, as well as calibration and mechanical errors. According to the World Meteorological Organization (WMO, 2008) the principal sources of inaccuracy of TB gauges are: evaporation and wetting losses, and wind-induced errors. Since errors in rainfall measurements can lead to the failure of hydraulic infrastructure or wrong conclusions in research (Willems, 2001), considerable international efforts were made to quantify and limit the uncertainty in rainfall measurements (Lanza and Stagi, 2008).

Several comparative studies have been conducted to define differences in the precipitation depth captured by rainfall gauges, and to develop guidelines for the correction of measurements. Since 1955, the WMO has conducted four international high-quality comparative studies (Sevruk et al., 2009) to assist the multiple users of rain gauges in the correct interpretation of precipitation measurements. In the WMO intercomparison studies (Sevruk and Hamon, 1984; Vuerich et al., 2009), data from pit gauges are used as reference for quantifying the deviations of the measurements of the sensors with respect to actual rainfall depth. Nonetheless, relative inter-comparison studies are also valuable, hence the extensive volume of literature dedicated to comparing the performance of rain sensors with varying technology, accuracy and resolution (Krajewski et al., 1998; Nešpor and Sevruk, 1999; Nystuen, 1999; Krajewski et al., 2006; Lanzinger et al., 2006; Rollenbeck et al., 2007; Duchon and Biddle, 2010). Even though more precise gauges are expected to overall perform better than less precise ones, the effect of rainfall intensity and wind conditions on the sensor measurements is still insufficiently known.

Comparative studies of rain gauges in tropical mountain areas are few. In the Andes, the longest continental mountain range in the world, one study has analyzed the performance of rain sensors in a tropical mountain forest in southeastern Ecuador located at an elevation of 1960 m a.s.l. (Rollenbeck et al., 2007), and another study analyzed the performance on rain gauges in a high-elevation tussock grassland ecosystem, locally called páramo, at 3780 m a.s.l. (Padrón et al., 2015) Both of these studies used specialized sensors, such as disdrometers and micro rain radars, that are rarely available at standard monitoring stations. Meanwhile, there are several monitoring initiatives in the highlands above 3000 m a.s.l., such as the Initiative for the Hydrological Monitoring of Andean Ecosystems (Iniciativa para el Monitoreo Hidrológico de Ecosistemas Andinos), a Northern Andes network of Non-Governmental Organizations, Public Institutions and universities that are conducting basic hydrological monitoring in small catchments as to gain knowledge about their hydrological functioning and the impacts of global change, and that use a variety of commercial rain gauges with different resolutions. Using these heterogeneous data can affect hydrological applications, highlighting the need to understand the differences between the gauges under the particular rainfall and climate conditions of the ecosystem.

This study assesses the relative performance between TB rain gauges in the páramo ecosystem in southeastern Ecuador. This ecosystem is a vital year-round water provider (for agricultural, urban and energy production purposes) for Ecuador, Colombia and Venezuela (Buytaert et al., 2006b,a; Célleri and Feyen, 2009; Ochoa-Tocachi et al., 2016), regions characterized by low intensity rains throughout the year. Specific aspects also studied are the effect of rainfall intensity and wind on the measurements of the tested rain gauges.

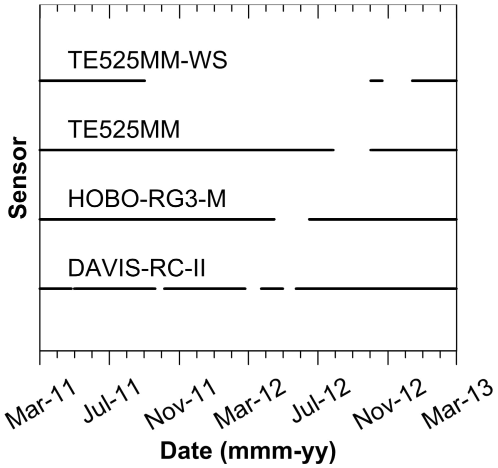

Figure 1. Available data of the Tipping-Bucket (TB) rain gauges used in the comparative analysis are depicted by continuous lines (gaps in the lines represent periods of missing observations).

2 Materials

Four tipping-bucket rain gauges were installed in the Zhurucay Ecohydrological Observatory, situated on the western cordillera of the Andes in southern Ecuador (3°03′S, 79°14′W): one Davis Rain Collector II (DAVIS-RC-II), one Hobo Data Logging Rain gauge RG3-M (HOBO-RG3-M), one TE525MM sensor (TE525MM) and one TE525MM gauge equipped with the 260-953 Alter-Type Wind Screen (TE525MM-WS). The windscreen consists of an iron-zinc shield concentric with the TB gauge. A full description with technical details of the windshield and installation considerations is available in previous studies (Alter, 1937; Duchon and Essenberg, 2001). Table 1 lists the main features of the four rain gauges used in the comparative study.

The tested rain sensors are commonly used in the Andean region for operational and research purposes, e.g. by the Ecuadorian National Institute of Meteorology and Hydrology (Instituto Nacional de Meteorología e Hidrología, INAMHI), the Initiative for the Hydrological Monitoring of Andean Ecosystems (Buytaert and Beven, 2011; Crespo et al., 2012; Muñoz et al., 2016, 2018; Sucozhañay and Célleri, 2018). The gauges were installed on a mutual distance of 2 m, with the surface area of the gauges opening 1 m above the ground surface, on an extended flat area, at an elevation of 3780 m a.s.l. Precipitation data were recorded during 2 years; the number of tips per minute was stored in an automatic data logging system for the TE525MM rain sensors, whereas for the other gauges the timestamp (hh:mm:ss) of each tip was recorded. The average temperature during the observation period was 6 $°C$, the relative humidity 91 % (Córdova et al., 2015), and the wind speed was on average 3 $m\ s^{-1}$ in the period October–April and 4.5 $m\ s^{-1}$ in the period May–September. Climate data were recorded with an interval of 5 minutes, in an adjacent automatic weather station.

The gauges were subjected to a static calibration, prior to installation. Given the low intensity of the frequent rains and in line with the findings of (Vasvári, 2005) and gauge manufacturer recommendations, the application of a dynamic calibration would be needless. Using a high-resolution pipette the real water volume to tip the bucket of the rain sensors was measured. The correction factor varied between $-6{,}56$ and $+4{,}29$ %. Due to a malfunctioning of the electronic connection to the datalogger for the TE525MM-WS, more than half of its data were disregarded. Figure 1 depicts the data available for each instrument; missing data varied between 8 and 10 % for the gauges DAVIS-RC-II, HOBO-RG3-M and TE525MM, and amounted to 61 % for the TE525M-WS gauge.

Table 1. Manufacturer specifications of the compared Tipping-Bucket (TB) rain gauges.

Sensor	Capturing diameter (cm)	Resolution (mm)	Intensity (mm h^{-1})	Accuracy (%)
DAVIS-RC-II	16.5	0.254	$0-50$	± 1
			$50-100$	± 5
HOBO-RG3-M	15.4	0.200	$0-20$	± 1
TE525MM TE525MM-WS	24.5	0.100	$0-10$	± 1
			$10-20$	$+0,-3$
			$20-30$	$+0,-5$

3 Methods

3.1 Statistical indices for the assessment

For the quantitative assessment of differences in performance between the rain gauges the following set of statistical indices, similar to that proposed by Tokay et al. (2010), was used: the coefficient of determination (R^2), the Spearman's non-parametric correlation (ρ), the standard deviation (σ), the percent bias and the percent absolute bias. The statistical indices were calculated with respect to the rain data collected by the TE525MM sensor. This sensor was considered in this study as reference because of its better technical features compared to the other rain gauges, and its larger data set compared to the TE525MM-WS. The percent bias and percent absolute bias, Equations (1) and (2) respectively, were calculated as follows:

$$percent\,bias = \frac{1}{\bar{y}}\left(\frac{1}{n}\sum_{i=1}^{n}(x_i - y_i)\right) \quad (1)$$

$$percent\,absolute\,bias = \frac{1}{\bar{y}}\left(\frac{1}{n}\sum_{i=1}^{n}|x_i - y_i|\right) \quad (2)$$

where x and y are defined as the precipitation depth registered by one of the gauges and the TE525MM for any time interval, n is the number of values or intervals with recorded rainfall, and $\bar{y}$ is the average precipitation depth measured by the TE525MM for the considered timescale. For rating the performance of the gauges the following categories of the percent bias were defined: excellent $\leq 2\%$, $2\% <$ good $\leq 5\%$, $5\% <$ regular $\leq 10\%$, and poor $>10\%$.

3.2 Overall performance

The precipitation records of the different gauges were compared to check if they were working properly. The functioning of a sensor was characterized by R^2 and ρ. The latter was calculated to test the validity of R^2 that normally is affected by the non-normal distribution of rainfall. For the TE525MM data at an hourly timescale, the non-normal distribution was confirmed by finding p-values of less than 0.01 for both the Kolmogorov-Smirnov and Shapiro-Wilk's tests. Nonetheless, R^2 was calculated to compare our results with those of other studies. To assess the effect of extreme values on R^2, the difference between ρ and R^2 was considered as indicator. According to Tokay et al. (2003); Rollenbeck et al. (2007); Tokay et al. (2010), R^2 values are expected to be greater than 0.95 for hourly and daily data from TB gauges located at the same site.

Following this, differences in precipitation depth were analyzed between each of the rain sensors and the reference gauge using the percent bias as indicator (Equation 1). Additionally, given the hydrological relevance of precipitation data for short timescales (Ciach, 2003; Rollenbeck et al., 2007; Buytaert and Beven, 2011), the accuracy of the rain gauges was also determined for respectively the 5 min, 10 min, 30 min, hourly and daily timescale. For this, absolute bias (obtained with Equation 2) was compared to regular bias, and this information was complemented with the standard deviation of the differences between measurements from the sensors (σ_{x-y}).

3.3 Rainfall intensity effect

For the assessment of the rainfall intensity effect on the accuracy of the rain gauges, measurements from the sensors corresponding to the following

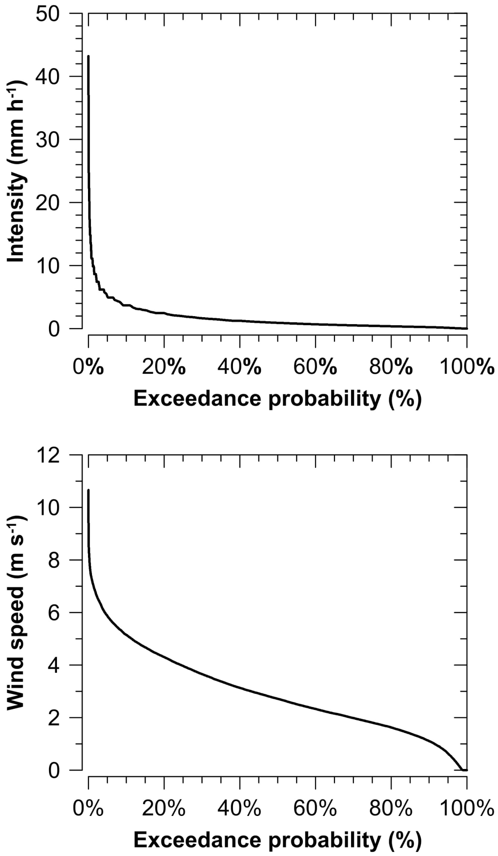

Figure 2. Rainfall intensity exceedance probability curve of the 5-min rainfall data collected by the TE525MM gauge (**top**), and wind speed exceedance probability curve of the corresponding 5-min intervals (**bottom**).

categories: 0–1 $mm\ h^{-1}$, 1.01–2 $mm\ h^{-1}$, 2.01–5 $mm\ h^{-1}$, 5.01–10 $mm\ h^{-1}$ and $>10\ mm\ h^{-1}$ were compared. These categories were established by trying to have for each of them a flat distribution, and a representative percentage of the total amount of data (Figure 2 top). For the separation of the data per intensity category, the intensities measured by the TE525MM gauge were within the limits of each specific category, whereas the corresponding intensities measured by the other gauges were not necessarily within these limits. For data belonging to each intensity category and timescales of 5, 10, 30, and 60 minutes, the percent absolute bias was computed to define the effect of these variables on the accuracy with which TB gauges estimate actual rainfall intensity. Percent bias was also calculated for the different intensity categories to understand and quantify how the deviations between the measurements of the gauges vary as a function of actual rainfall intensity.

The intervals with rain intensities for the comparison were between exact hours, without time overlap and with rain during their entire length. For example, for an event that had its first tip at 19:08 UTC and its last one at 21:17 UTC of the same day, the used intervals for a 30 minute timescale were: 19:30–20:00, 20:00–20:30, and 20:30–21:00 UTC. The intervals 19:00–19:30 and 21:00–21:30 UTC were discarded because it did not rain during the entire interval. Although, this approach reduced the volume of data, the useable dataset was still very representative—e.g. for the 5 min timescale the cumulative rainfall of the used intervals represented 85 % of the total precipitation volume of the TE525MM database.

3.4 Wind speed effect

Only the effect of wind speed on the accuracy of the rain gauges was analyzed because there were not any evident obstacles to suggest an effect of wind direction. Similar criteria as for the rainfall intensities were used to classify wind speed (Figure 2 bottom), establishing the following categories: 0–2 $m\ s^{-1}$, 2.01–4 $m\ s^{-1}$ and 4 $m\ s^{-1}$. The wind speed data and selected categories are similar to those used by Sevruk and Hamon (1984) in their worldwide study. Also, wind speeds registered in other mountain highlands, like the Swiss-Austrian Alps or the Bolivian Altiplano, did not differ much from the recorded wind speeds for the páramo (Vacher et al., 1994; Draxl and Mayr, 2009). Percent bias and percent absolute bias were used for the data corresponding to each category to analyze the effect of wind speed on the measurements from the sensors.

The selected timescale had to provide good accuracy of the precipitation depth captured by each gauge, while assuring at the same time that a sufficient amount of data per wind speed category was available. The accuracy requirement was determined from the overall assessment and intensity effect analyses. To distinguish the individual effect of wind from the effect of rainfall intensity, the distribution of the rainfall intensity data corresponding to each of the wind speed categories was determined. The rain depth intervals for the comparison of the sensors with respect to the effect of wind were selected employing the same criteria used for doing this when examining the effect of rainfall intensity—i.e. intervals between exact hours, without time overlap and with rain during their entire length.

4 Results and Discussion

4.1 Overall performance

Table 2 depicts the coefficient of determination $\left(R^2\right)$ and the Spearman's correlation (ρ) of the DAVIS-RC-II, HOBO-RG3-M and TE525MM-WS gauges with respect to the precipitation recorded by the TE525MM sensor. Both coefficients are presented for the timescales 5, 10 and 30 min, hourly and daily. The data clearly reveal that the value of R^2 and ρ increases with timescale, which according to Nystuen (1999) is due to the fact that for longer intervals it is less important how it rains. This also illustrates that the importance of accuracy and resolution of the rain gauges is more relevant for time aggregations of 30 minutes or less. Values of R^2 tend to suggest a better agreement between sensors than expected, due to the effect that extreme values have on this index. This effect can be seen clearly for the 5 and 10 minute timescales, where R^2 is much higher than ρ. Correlations between all gauges and the TE525MM were statistically significant; the probability that measurements from two different gauges were not correlated was always less than 1 % ($p<0.01$). Several other studies (Tokay et al., 2003; Rollenbeck et al., 2007; Tokay et al., 2010) also found high correlations ($R^2 > 0.95$) between the measurements of two side-by-side gauges for respectively hourly and daily timescales.

The percent bias of the difference between the total precipitation captured by the three gauges relative to the TE525MM gauge, which is independent of the used timescale, varied among −7,2 % (DAVIS-RC-II), −5,6 % (HOBO-RG-3) and −2 % (TE525MM-WS). The negative values indicate an underestimation of the gauges in relation to rainfall volume caught by the reference sensor. Based on the aforementioned criteria, the performance of the DAVIS-RC-II and HOBO-RG-3 gauges is regular, whereas that of the TE525MM-WS is excellent. The obtained results are in line with the deviation range found by Rollenbeck et al. (2007) for gauges from different manufacturers, and by Tokay et al. (2003, 2010) for identical gauges.

Figure 3 shows the percent absolute bias of the TB gauges as a function of the timescale. There is a clear influence of gauge resolution, with the DAVIS-RC-II sensor having the largest percent absolute bias and the coarsest resolution. There is also an effect of timescale on the gauges' accuracy that can be explained by the fact that during short intervals, given the overall low rainfall intensity, some sensors do not register rain, while others do, and in the next time interval the opposite often occurs. Indeed, in nearly 50 % of all 5 min intervals considered, when one of the compared TB gauges recor-

Table 2. Coefficient of determination $\left(R^2\right)$ and Spearman's correlation coefficient (ρ) for the Tipping-Bucket (TB) rain gauges in relation to the TE525MM sensor for different timescales

Sensor	Timescale	R^2	ρ
DAVIS-RC-II	5 min	0.603	0.364
HOBO-RG3-M		0.690	0.395
TE525MM-WS		0.809	0.495
DAVIS-RC-II	10 min	0.826	0.590
HOBO-RG3-M		0.876	0.624
TE525MM-WS		0.933	0.716
DAVIS-RC-II	30 min	0.953	0.792
HOBO-RG3-M		0.969	0.826
TE525MM-WS		0.986	0.887
DAVIS-RC-II	hourly	0.975	0.860
HOBO-RG3-M		0.985	0.893
TE525MM-WS		0.993	0.935
DAVIS-RC-II	daily	0.993	0.992
HOBO-RG3-M		0.997	0.996
TE525MM-WS		0.997	0.997

ded precipitation the other did not. For hourly and shorter timescales the standard deviation of the differences with the TE525MM were smaller than the resolution of the sensors; values of 0.165 *mm*, 0.130 *mm* and 0.085 *mm* were obtained respectively for the DAVIS-RC-II, HOBO-RG3-M and TE525MM-WS gauges at the hourly timescale. These results imply that in regions with frequent low-intensity rains such as the wet páramo, and when interested in rainfall behavior during time periods of 1 hour or less, the importance of sensor resolution is strongly amplified.

4.2 Rainfall intensity effect

As evidenced by values of percent absolute bias in Table 3, the accuracy of the rain gauges decreases significantly for low intensities and short timescales. This reduction in accuracy (expressed as percentage) happens under the mentioned conditions because precipitation depth is extremely low, boosting the effect of gauge resolution. However, accuracy is still especially poor for rainfall intensities of 2 $mm\ h^{-1}$ or less (which are typical conditions, as shown in Figure 2) and timescales of 10 minutes or shorter. These results agree well with the findings from Habib et al. (2001); Ciach (2003); Wang et al. (2008).

Considerable errors between actual and calculated rainfall intensity affect the analysis of how the deviations between the measurements of the gauges vary depending on rainfall intensity. Therefore, different timescales for each intensity category had to be used to obtain data with acceptable accuracy, while still counting with an appropriate number of time intervals for which rainfall was measured by the sensors. The data categories with bold text in Table 3 were used to determine the percent bias of the TB gauges, in relation to the TE525MM gauge, for the different intensity categories (Figure 4).

Percent bias results depict a general tendency of higher values for lower intensities and coarser gauge resolution. The results for the DAVIS-RC-II correspond to a poor performance for the lowest intensity category, and a regular rating for all other categories. For the HOBO-RG3-M, the value of the percent bias was near the transition from regular to good performance for intensities $\leq 5\ mm\ h^{-1}$, and corresponded to an excellent rating for intensities >5 $mm\ h^{-1}$. The TE525MM and TE525MM-WS gauges registered very similar measurements for all intensities, but performance was rated good for the ≤ 1 $mm\ h^{-1}$ category, and excellent for all other catego-

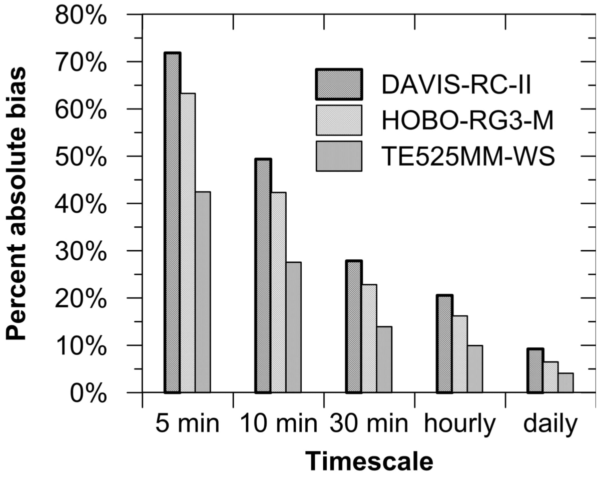

Figure 3. Percent absolute bias of the Tipping-Bucket (TB) rain gauges in relation to the TE525MM sensor as a function of timescale.

ries. As a general conclusion, the larger value of the percent bias for lower intensities is attributed to intrinsic features of the studied gauges that influence wetting and evaporation losses (WMO, 2008). It is important to notice that an overall comparison of the same TB gauges used in this study at a location with rainfall intensities different from those typical of the páramo, would reveal completely different results.

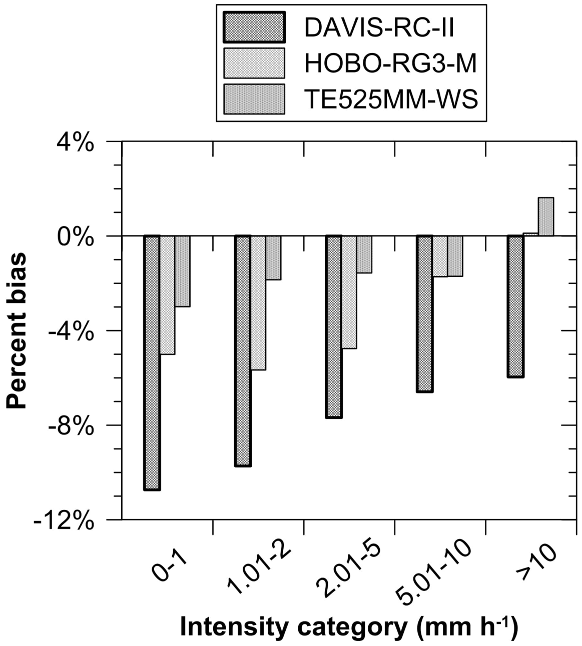

Figure 4. Percent bias of the Tipping-Bucket (TB) rain gauges in relation to the TE525MM sensor as a function of rainfall intensity. The data used for this figure corresponds to the highlighted categories in Table 3.

Table 3. Percent absolute bias (%) and number of data points (#) per intensity category and timescale, for each of the Tipping-Bucket (TB) rain gauges in relation to the TE525MM sensor.

Intensity category (mm h^{-1})	Timescale							
	5 min		10 min		30 min		60 min	
	DAVIS-RC-II							
	%	#	%	#	%	#	%	#
$0-1$	72	4864	56	2192	27	549	**15**	**165**
$1.01-2$	37	2618	29	1341	**14**	**411**	13	181
$2.01-5$	25	2492	16	1170	**10**	**320**	8	111
$5.01-10$	17	530	12	255	**7**	**50**	7	18
> 10	12	158	**10**	**62**	4	10	5	2
	HOBO-RG3-M							
	%	#	%	#	%	#	%	#
$0-1$	62	5130	47	2323	18	580	**10**	**180**
$1.01-2$	30	2569	20	1325	**10**	**404**	8	181
$2.01-5$	20	2444	12	1169	**7**	**322**	6	112
$5.01-10$	16	520	10	256	**4**	**49**	4	18
> 10	12	155	**8**	**62**	4	10	2	2
	TE525MM-WS							
	%	#	%	#	%	#	%	#
$0-1$	39	3000	27	1325	10	334	**7**	**105**
$1.01-2$	20	1537	11	799	**6**	**254**	5	120
$2.01-5$	12	1338	7	618	**4**	**171**	3	62
$5.01-10$	9	260	**4**	**122**	3	28	2	8
> 10	**4**	**71**	4	29	2	4	3	2

Note: Categories with **bold** text were used for the percent bias analysis in Figure 4.

4.3 Wind speed effect

The percent bias and percent absolute bias of the TB gauges in comparison with the TE525MM sensor were calculated for each wind speed category (Table 4), using the 30-min data. This timescale was used since it provided an acceptable accuracy for estimating rainfall intensity, and because a sufficient amount of 30-min rainfall data was available. The absolute percent bias showed an increment for all the gauges when wind speed was greater than 4 $m\ s^{-1}$. This surprising behavior is most likely related to the fact that rainfall intensities, in general, were lower for the highest wind speed category (Mekonnen et al., 2014). The percent bias results for the DAVIS-RC-II and HOBO-RG3-M gauges hardly change for the different wind speed categories. This does not mean that those gauges are not prone to wind-induced errors; instead it shows that these errors are practically identical for the DAVIS-RC-II, the HOBO-RG3-M and TE525MM sensors. We hypothesize that the similarity in shape, dimension and installation heights of the gauges generate a similar airflow around them, leading to dismissible differences between the sensors due to wind speed (Nešpor and Sevruk, 1999).

Given the presence of an Alter-Type windshield around the TE525MM-WS sensor, a noticeable difference in rainfall depth may have been expected with the technologically identical gauge (TE525MM) without windshield. A dismissible bias, less than 1 %, was found for the precipitation data that occurred with wind speeds $\leq 4\ m\ s^{-1}$, suggesting that the Alter windshield does not really reduce the under catch of rainfall in the páramo for these wind speed conditions. A similar result was found by Duchon and Essenberg (2001), although at a site likely with a different rainfall drop size distribution. Moreover, Duchon and Biddle (2010) concluded that the Alter windshield does not significantly reduce wind-induced errors by also using a ground-level gauge. Meanwhile, for wind speeds $>4\ m\ s^{-1}$, results show that the shielded gauge recorded even less precipitation than the unshielded gauge.

Table 4. Percent bias and percent absolute bias per wind speed category for each of the Tipping-Bucket (TB) rain gauges in relation to the TE525MM sensor.

Wind speed (ms^{-1})	DAVIS-RC-II		HOBO-RG3-M		TE525MM-WS	
	% bias	% absolute bias	% bias	% absolute bias	% bias	% absolute bias
$0-2$	-8.6	11.4	-4.3	8.1	-0.2	3.7
$2.01-4$	-8.2	12.2	-4.4	8.2	-0.7	5.0
>4	-8.4	16.7	-2.4	11.0	-6.6	9.0

5 Conclusions

The performance of four tipping-bucket rain gauges, installed side by side in an Andean headwater catchment, was analyzed using 2-year data. The installation site is situated in the tropical Andes, southern Ecuador, at an elevation of 3780 m a.s.l., and is representative for the wet páramo region. Rain events are most of the time characterized by a low intensity: 95%, 76%, and 53% of the 5-min intervals have intensities lower than 5, 2, and 1 $mm\ h^{-1}$, respectively. These rainfall characteristics differentiate the present research from previous intercomparison studies. In addition for the study site, precipitation intensities are lower than average under windy conditions (4 $m\ s^{-1}$), which occur during 25% of the rainfall events.

A clear relation between gauge resolution and total precipitation depth was found: a coarser resolution corresponds to less registered rainfall depth. The results showed an underestimation of 7.2% and 5.6% for gauges with a resolution of 0.254 *mm* and 0.2 *mm* respectively, when compared to a gauge with 0.1 *mm* resolution. The differences between the sensors are principally attributed to a combination of wetting and evaporation losses, because of the relation between these sources of error and gauge resolution. The higher underestimation of the DAVIS-RC-II gauge could be related to higher evaporation caused by the black color of the funnel absorbing more ambient heat. Additionally, evaporation losses are boosted by the frequent low-intensity rain events.

It was found to be very common for timescales of 5 and 10 minutes that a TB gauge registers a tip within an interval when another gauge does not for that same interval, but for the one that follows. This phenomenon caused results to show an extreme difference among sensors when actual differences in measured precipitation depth were much lower. Therefore, sensor resolution is a critical aspect to consider for rainfall monitoring in the wet páramo, or any other ecosystem with similar precipitation characteristics.

Wind speed has a similar effect on the analyzed unshielded TB gauges. Meanwhile, the Alter windshield did not reduce wind-induced losses.

The quantitative knowledge of the differences between the sensors obtained in this study is an important step to homogenize rainfall data from multiple sites within the Andean highlands. Additionally, the fact that rainfall in the wet páramo is underestimated in at least 5% by commonly used gauges is pivotal for water-related studies in these landscapes and guide the selection of adequate equipment for monitoring networks.

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