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Assessment of snowfall accumulation underestimation by tipping bucket gauges in the Spanish operational network

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Abstract. Within the framework of the World Meteorological Organization Solid Precipitation Intercomparison Experiment (WMO-SPICE), the Thies tipping bucket precipitation gauge was assessed against the SPICE reference configuration at the Formigal–Sarrios test site located in the Pyrenees mountain range of Spain. The Thies gauge is the most widely used precipitation gauge by the Spanish Meteorological State Agency (AEMET) for the measurement of all precipitation types including snow. It is therefore critical that its performance is characterized. The first objective of this study is to derive transfer functions based on the relationships between catch ratio and wind speed and temperature. Multiple linear regression was applied to 1 and 3 h accumulation periods, confirming that wind is the most dominant environmental variable affecting the gauge catch efficiency, especially during snowfall events. At wind speeds of 1.5 m s^{-1} the tipping bucket recorded only 70 % of the reference precipitation. At 3 m s^{-1}, the amount of measured precipitation decreased to 50 % of the reference, was even lower for temperatures colder than −2 °C and decreased to 20 % or less for higher wind speeds.

The implications of precipitation underestimation for areas in northern Spain are discussed within the context of the present analysis, by applying the transfer function developed at the Formigal–Sarrios and using results from previous studies.

1 Introduction

Variability of snowfall accumulation strongly influences the ecology and hydrology of mountainous areas and cold regions, impacting economic activities including winter tourism, hydropower generation, floods and water supply for agriculture. (Beniston, 2003; Barnett et al., 2005; Lasanta et al., 2007; Mellander et al., 2007; Jonas et al., 2008a, b; Uhlmann et al., 2009). For this reason, an accurate measurement of snowfall accumulation is critical. Moreover, suitable snowfall warnings based on reliable real-time data must be issued by the National Weather Services because snowfall disrupts transport, increases the number of traffic accidents and injuries and affects the normal function of infrastructures in inhabited areas.

It is well known that the undercatch of solid precipitation resulting from wind effects at gauge orifices is the main factor affecting the quality and accuracy of measured amounts of solid precipitation (Goodison et al., 1998). This effect can be reduced by the use of different wind shields; however, a bias still remains, and an adjustment is needed. To derive adjustment functions for different gauge and shield configurations, the test gauge needs to be compared against a standard reference configuration. During the first World Meteorological Organization (WMO) Solid Precipitation Intercomparison (Goodison and Metcalfe, 1992; Goodison et al., 1998; Yang et al., 1995, 1998a, b), the World Meteorological Organization (WMO) defined the Double Fence Intercomparison Reference (DFIR) as a secondary reference for solid precipitation to be used for intercomparisons. The DFIR consists of two concentric, octagonal wind fences paired with a manual Tretyakov precipitation gauge and wind shield (Goodison et al., 1998). Due to modernization and automation of the many different national operational networks, the variation in instrumentation has increased in the last two decades (Nitu and Wong, 2010), making it more difficult to intercompare long climate data series from different countries (Scaff et al., 2015). This is one of the reasons why a WMO Commission for Instruments and Methods of Observations (CIMO) multisite intercomparison of instruments for the measurement of solid precipitation was initiated in 2012.

The focus of the World Meteorological Organization Solid Precipitation Intercomparison Experiment (WMO-SPICE) is on assessing the performance of different types of automatic precipitation gauges and configurations in different climate regimes. WMO-SPICE has defined a reference configuration with a DFIR shield and a single-Alter shielded automatic precipitation gauge (Geonor T200-B3 or OTT Pluvio^2) in the centre; this is called the Double Fence Automatic Reference (DFAR; SPICE-IOC, 2012). Recent studies using this configuration as a reference can be found in the literature (Smith and Yang, 2010; Rasmussen et al., 2012, 2014; Wolff et al., 2014, 2015; Kochendorfer et al., 2017).

Numerous studies have been conducted that have focused on the spatial variability and trends of precipitation in Spain (Begueria et al., 2009; Vicente-Serrano et al., 2011, 2015; Lopez-Moreno et al., 2010; Cortesi et al., 2014; El-Kenawy et al., 2012; Buisan et al., 2016a). All of these studies have used long-term data from Hellman gauges and, more recently, from automated tipping bucket gauges, which are the main subject of this study. With the relatively recent switch from manual gauges to the automated tipping bucket, it is now critical that both the science and operational communities have a clear understanding of how these gauges measure winter precipitation. Data users must be aware of the underestimation of precipitation during snowfall events, especially in windy environments, and be able to identify areas where the impact of underestimation is higher.

To facilitate precipitation gauge intercomparison experiments in Spain, a WMO-SPICE site has been established by AEMET (Spanish State Meteorological Agency) at Formigal–Sarrios (Figs. 1 and 2), located in the Pyrenees range (Latitude: 42.76°, Longitude: −0.39°). This site features a weighing gauge in a DFAR configuration, with additional weighing gauges in single-Alter and unshielded configurations. A Thies automatic tipping bucket gauge – the most widely used gauge for the measurement of precipitation by automatic weather stations (AWSs) in Spain – has been installed for comparison against the DFAR configuration.

The objective of this work is to assess the reliability and performance of the Thies automated tipping bucket gauge used in the Spanish operational network and to demonstrate the importance of accurate snowfall measurements within this network. A transfer function for the estimation of snowfall amounts by this gauge is derived from the comparison against the DFAR. Wind speed and temperature data during snowfall events were used in this analysis to help determine the potential impact of wind-induced undercatch on Spanish snowfall measurements. These results are used to identify areas within Spain where errors affecting snowfall accumulation are most significant.

2 Methodology

2.1 Test site and instruments

The Formigal–Sarrios test site is located on a small plateau at 1800 m a.s.l. in the Pyrenees mountain range (Fig. 1). This is an alpine environment, consisting of a mixture of bare ground and only very low grasses. Snowfalls are frequent, with maximum measured snow depths of almost 300 cm during the 2013–2014 and 2014–2015 winter seasons. Southerly and south-westerly snowfall events are typically associated with light winds and mild temperatures (at approximately 0 °C) whereas northerly and north-westerly snowfalls are typically associated with strong winds and colder temperatures (< -2 °C).

Table 1 shows the list of instruments under test. The automatic weighing gauge used in reference configurations is an OTT Pluvio^2 gauge (OTT Hydromet, Kempten, Germany) with a 200 cm^2 orifice area and 1500 mm capacity. Within the framework of SPICE, these gauges were used in two reference configurations: (1) shielded (single Alter, SA) inside a DFIR fence and referred to as the DFAR or R2 reference, and (2) as a shielded (SA) and unshielded (UN) pair and referred to as the R3 reference. A disdrometer (Laser Precipitation Monitor, Thies Clima, Göttingen, Germany) was also in-

Table 1. List of instruments being tested at the Formigal–Sarrios WMO-SPICE site.

Instrument (Manufacturer)	Configuration	Reference	Variable used	Acronyms
Weighing gauge Pluvio^2 (OTT)	DFIR	R2	TNRT	DFAR
Disdrometer LaserPM (Thies)	DFIR	R2	Intensity total precipitation	LPM
Weighing gauge Pluvio^2 (OTT)	Single Alter	R3	TNRT	SA
Weighing gauge Pluvio^2 (OTT)	Unshielded	R3	TNRT	UN
Tipping bucket (Thies)	Unshielded	AEMET Network	Standard	TPB

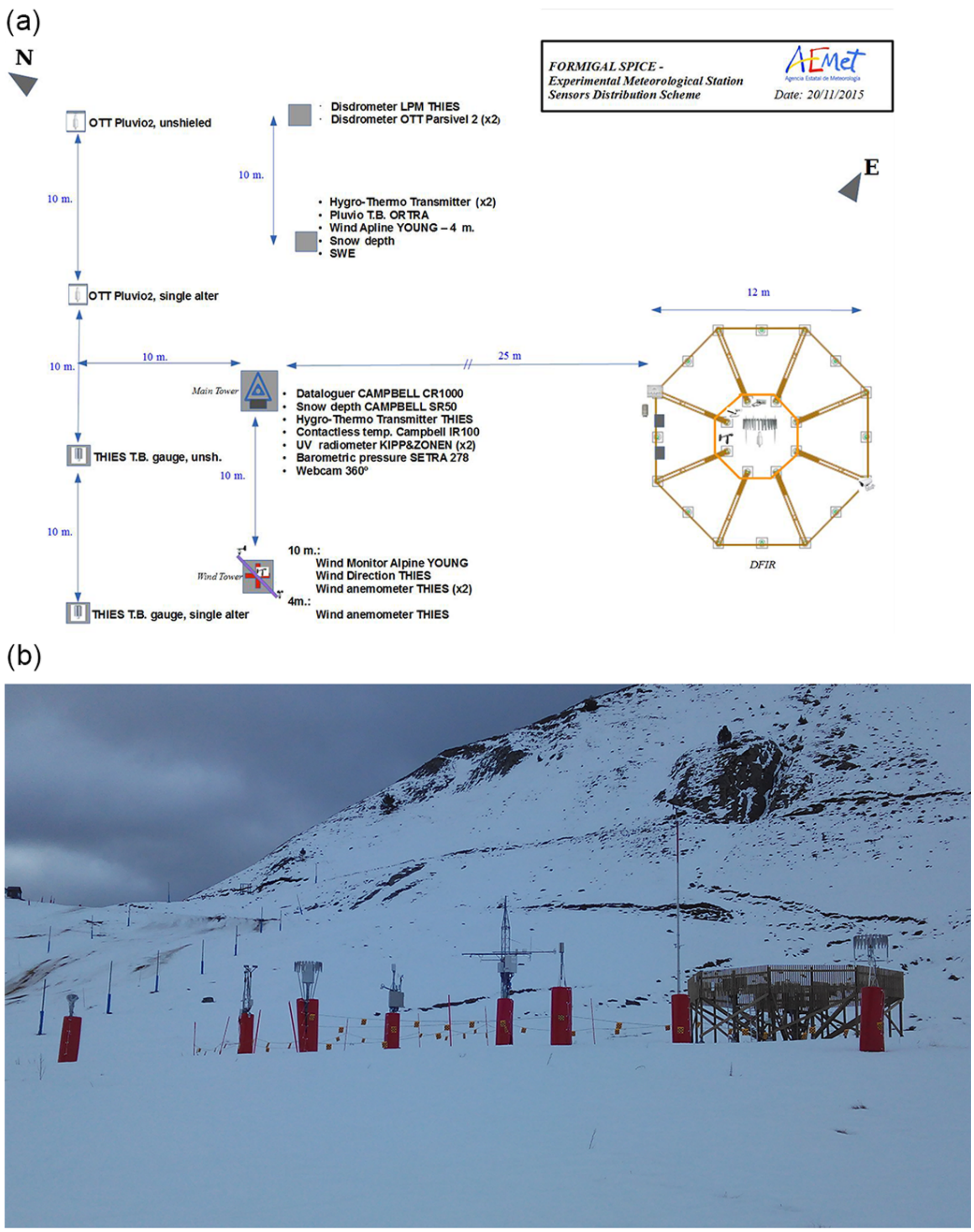

Figure 1. Layout **(a)** and photograph **(b)** of the Formigal–Sarrios test site.

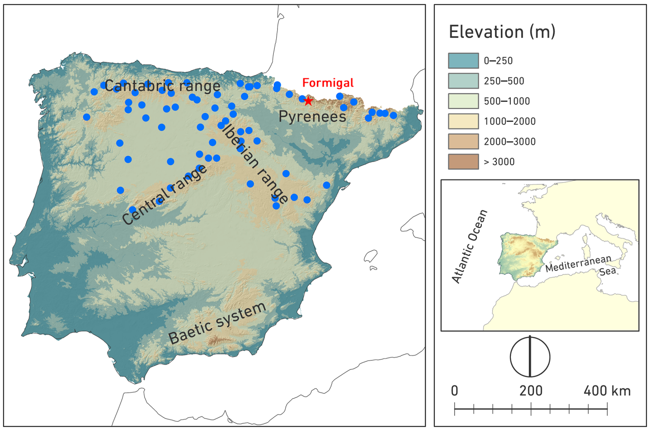

Figure 2. Orography of Spain and location of the Formigal–Sarrios site. Blue points indicate the location of automatic weather stations in the operational network.

stalled inside the DFAR. The tipping bucket (TPB) under test was a heated gauge (Precipitation Transmitter, Thies Clima, Göttingen, Germany) with a heating power of 49 W. This TPB is used in approximately 80 % of the automatic weather stations (AWSs) in the AEMET operational network. The Pluvio^2 output parameter used in this analysis was the "non-real-time" or NRT accumulation.

As described in the Pluvio^2 manual, the NRT output was used because in this mode the instrument collects fine precipitation using an integrated 0.2 mm per hour threshold, making it more comparable to the Thies tipping bucket gauge, which also has a minimum resolution of 0.2 mm. The outputs used from the Thies LPM disdrometer, which is also widely used at AEMET, included the precipitation intensity, total accumulation and precipitation type (the 1 min METeorological Aerodrome Report or METAR code).

Figure 1 shows the site and the distribution of instruments on the site. The height of the gauge orifice for all precipitation gauges and the disdrometer was 3.5 m. Two webcams provided real-time images of all instruments and enabled the detection of any problems, such as snow capping of gauge orifices or freezing rain.

Air temperature was measured with a PT100 from Thies and was protected by an unaspirated standard radiation screen at a height of 4.5 m. Wind was measured at a standard height of 10 m with a heated anemometer (Wind sensor, Thies Clima, Göttingen, Germany). These instruments are the same as those used in a standard AWS at AEMET. Integrated data were delivered every 1 min for all instruments and recorded using two Campbell CR1000 data loggers. The sampling frequency was different depending on the instrument, according to WMO guidelines.

A large number of snowfall events occurred during the 2014–2015 winter (December to April), providing a sufficient quantity of data for analysis. To assure high data quality, the quality control procedures removed all capping events and filtered out periods (1 and 3 h) in which less than 90 % of the 1 min precipitation data were available. All events considered as doubtful or erroneous were removed.

2.2 Features of the operational network of AEMET automatic weather stations

The orography of northern Spain, an area where the probability of snowfall is higher relative to other areas of Spain, is quite complex in terms of elevation, with an elevated plateau in the centre and numerous mountain ranges and basins surrounding the plateau (Fig. 2). The northernmost part of northern Spain, within the Pyrenees and the north side of Cantabrian Range, is characterized by narrow valleys. This region is mountainous, with numerous peaks above 3000 m a.s.l. Minor ranges such as the Iberian and Central Iberian ranges also surround the plateau, but these areas are more tabular, with less dramatic changes in elevation. In this area, the villages tend to be located in more open areas and often at a higher elevation than in the Pyrenees and Cantabrian Range, where habitation is largely in the valleys.

The AWS in the AEMET operational network are mainly located in villages and are installed according to WMO recommendations (WMO CIMO Guide, 2010). For this reason, the stations are usually in open flat areas far from obstacles (such as buildings and trees). However, during snowfall events, these locations often experience windier conditions due to exposure, which tends to result in increased undercatch of precipitation.

The long-term historical precipitation record in Spain relies mainly on Hellman rain gauges managed by collaborators, but in order to assure the continuation of these records, these gauges have been progressively replaced by automatic gauges, which are mainly tipping-bucket type gauges. The historical climate data used in this analysis to characterize automated snowfall measurement errors were retrieved from the national archive. All temperature, wind, relative humidity and precipitation data from the AEMET network are sent daily to the National Climatic Data Center, where 10 min data are available from 2009 onwards.

Automatic weather stations were not equipped with disdrometers; thus we used temperature data to select snowfall events. For the purpose of this analysis, snowfall events were defined as precipitation events that occurred when the average maximum temperature was colder than 0 °C and the total accumulation was greater than 0 mm during a 1 h time period. We consider these criteria to be adequate for the scope of this work, despite the fact that mixed precipitation can be observed at temperatures colder than 0 °C and that snow can fall at air temperatures warmer than 0 °C (Fassnacht et al., 2013).

Event selection was focused on data from northern Spain from January 2010 to April 2015, as it is the area with the highest frequency of snowfall (and therefore the most snowfall data for analysis). The locations with more winter precipitation on average are located north of the Cantabrian Range and in the westerns areas of the Pyrenees (Pons et al., 2010; Bootey et al., 2013; Buisan et al., 2014). The selection of specific AWS within this area was limited to those for which the TPB and anemometer were heated, and the number of hourly snowfall events was greater than 75.

3 Results

3.1 Intercomparison of the tipping bucket with the references

Figure 3 shows time series of accumulated precipitation measured at the Formigal–Sarrios test field site for two different types of weather conditions. These plots are based on 1 min data, instead of on averages over longer periods of time, as considered in the previous WMO solid precipitation intercomparison (Goodison et al., 1998). This higher temporal resolution allows one to see the evolution of the accumulation reported by different gauges and the effects of precipitation intensity, wind speed and temperature variations with greater detail. Figure 3a shows a typical snowfall event occurring within a southerly flow characterized by mild temperatures and light winds. In this situation, the differences in snowfall accumulation between the instruments located inside the DFIR and the UN and TPB were less than 20 %, while the difference with the SA was approximately 10 %. Figure 3b shows that under colder temperatures and stronger winds (up to $10\,\mathrm{m\,s^{-1}}$ or $36\,\mathrm{km\,h^{-1}}$), the differences in accumulation relative to the reference were significantly higher, with collection efficiencies of approximately 65, 60 and 45 % for the TPB, UN and SA respectively. In both situations, there is good agreement between the instruments DFAR and LPM which agree to within 10 (Fig. 3b) and 1 % (Fig. 3a) and good overall agreement in terms of the timing of the accumulations reported by each instrument. Deviations in accumulations from a given gauge are caused mainly by wind-induced undercatch and precipitation type (i.e. dry snow or wet snow).

Figure 4 shows the number of cases classified by type of precipitation at 1 min resolution as detected by the disdrometer during the 2014–2015 winter season. Results showed that for precipitation events at temperatures colder than 0 °C, precipitation occurred primarily as snow, with only a few cases of mixed precipitation. The number of cases for which snow was detected at temperatures warmer than 0 °C was still very high, which indicates that the threshold temperature of 0 °C was suitable, based on disdrometer data, for classifying the precipitation as snow and not rain for the site. The number of rain cases at temperatures between 0 and 2 °C was very low. Finally, at temperatures warmer than 2 °C, almost all precipitation events were in the form of rain.

The accumulated precipitation was calculated for the DFAR and tipping bucket for each 1 h period, provided that

Table 2. Contingency tables of cases detected by each instrument over 1 (top table) and 3 h (bottom table) accumulation periods. The sum of total accumulation measured by each instrument is provided in parentheses. Note that the amount provided for the yes/yes case represents the precipitation amount measured by the reference.

1 h period	DFAR yes	DFAR no
TPB yes	238 (400.33 mm)	11 (2.6 mm)
TPB no	156 (45.11 mm)	
3 h period	**DFAR yes**	**DFAR no**
TPB yes	96 (385.58 mm)	6 (1.6 mm)
TPB no	41 (15.62 mm)	

the average temperature was colder than 0 °C during this period. An accumulation period of 1 h was chosen because it was considered long enough to melt snow in the funnel of the tipping bucket, but still short enough to avoid large changes in temperature and wind speed used to characterize each time period. The lower catch of the TPB relative to DFAR may actually help to improve the temporal response of the TPB, because there is less precipitation to melt during each 1 h period. Figure 5a shows that during the experiment, the tipping bucket reported less than half of the precipitation reported by the DFAR. The contingency table (Table 2) shows that the tipping bucket only detected about 60 % of the 1 h precipitation events measured by the reference, while the DFAR only failed to detect about 2 % of cases that were only detected by the TPB. The accumulated DFAR precipitation during periods when TPB detection failed was only 10 % of the total seasonal precipitation, as the undetected periods typically occurred during light precipitation.

When the TPB accumulated more precipitation in a 1 h period than the DFAR, a catch ratio (TPB/DFAR) >1 resulted. These catch ratios >1 likely occurred due to the delay in the melting of the snow caught by the TPB. For example, if the DFAR reports accumulation during a given 1 h period, this delay can cause the TPB to report precipitation during a subsequent 1 h period, potentially resulting in catch ratios >1 for the subsequent 1 h period. Figure 5b shows that in 13 % of the cases, the catch ratio (TPB/DFAR) was >1 and that these cases accounted for 9.5 % of the total precipitation recorded by the tipping bucket. Therefore, based on the hypothesis that these ratios >1 are not likely physically realistic, the differences can be attributed to a time delay in the melting process within the bucket. This result could be considered as the percentage, on average, that is melted in the next hour. However, it is a low correction value in comparison with the differences due to the wind effect over the catch efficiency of the bucket.

To derive a suitable transfer function, only those events for which both the TPB and the DFAR detected precipitation and the TPB/DFAR catch ratio was lower than 1 were considered. Figure 6 shows the relationship between this catch ratio and wind speed. At wind speeds lower than $2\,\mathrm{m\,s^{-1}}$, the average

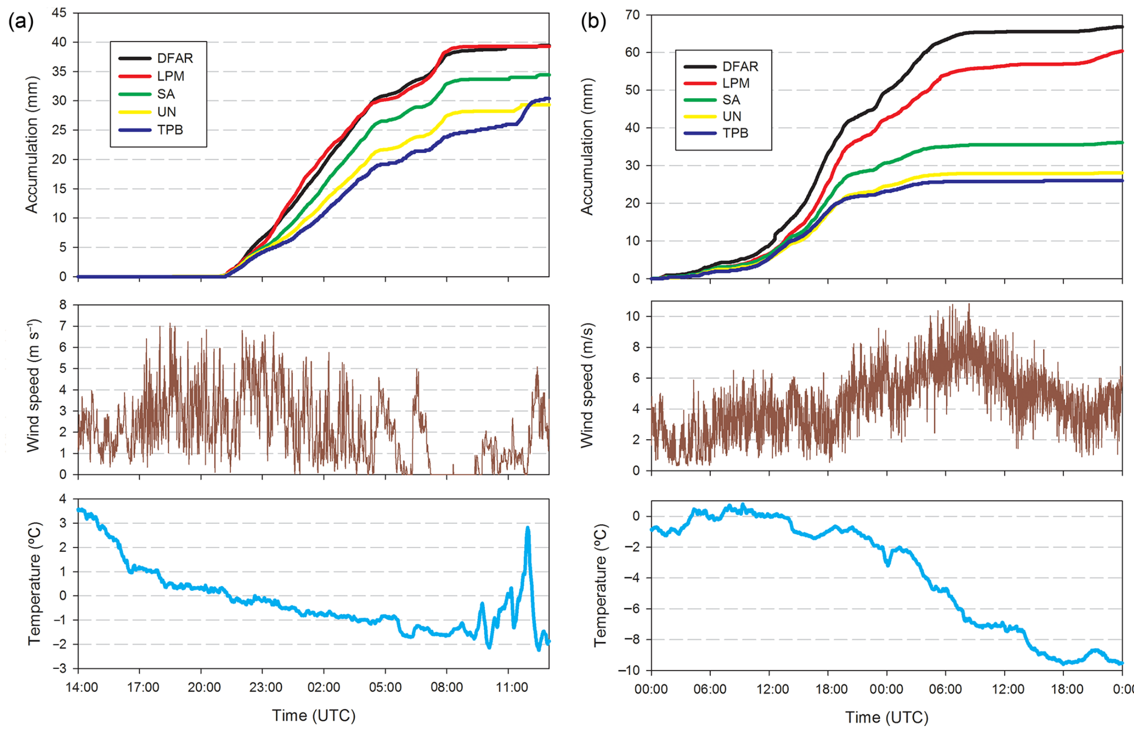

Figure 3. Accumulated precipitation, wind speed and temperature at Formigal–Sarrios during snowfall events on **(a)** 16–17 January 2015 and **(b)** 26–28 December 2014.

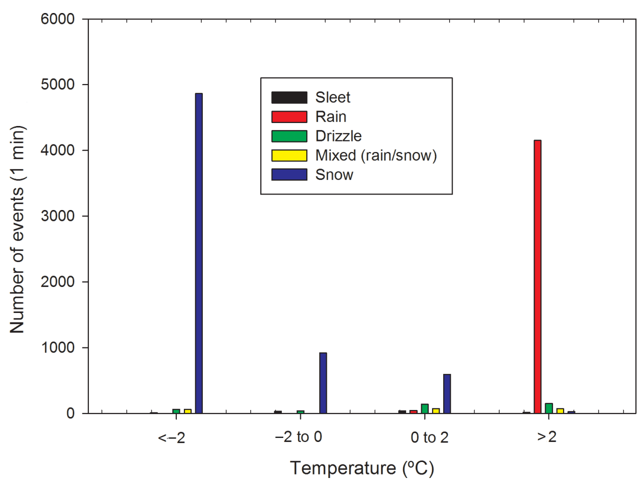

Figure 4. Frequency distribution of precipitation type binned by temperature using 1 min data derived from the disdrometer.

catch ratio is between 0.7 and 0.8. At higher wind speeds, the catch ratio decreases dramatically, reaching values lower than 0.2 at wind speeds higher than 5–6 $\mathrm{m\,s^{-1}}$. The decrease in the catch ratio for wind speeds of warmer events is not as fast as for the cold events.

Given the non-linear dependence of catch ratio on wind speed and, following a similar procedure from recent studies (Goodison et al., 1998; Rasmussen et al., 2012; Theriault et al., 2012; Wolff et al., 2015), an exponential curve was fit to the snow event data. Wind speed was found to explain more than 50 % of the variance. However, as shown in Fig. 6, at temperatures colder than −4 °C and wind speeds higher than 4 $\mathrm{m\,s^{-1}}$, this adjustment function slightly overestimates the catch ratio. For this reason, to derive more accurate relationships among catch ratio, wind speed, temperature and accumulation (intensity), a multiple regression analysis was applied (Table 3).

Since it is not possible to know operationally how much snow is melted from the previous hour of precipitation, and in order to derive an operational transfer function, we propose the following approach: implement a "melting factor" of 0.095 to correct for the average amount of snowfall that falls in the current hour but is not melted until the next hour. This value was determined by calculating the correlation between the hourly TPB measurements and the DFAR measurements for all "melting factors" between 0 and 30 %, and then creating a correlogram (Fig. 7). A peak in the correlation was associated with a melting factor of 9.5 %, where 9.5 % of the Thies precipitation from a given hour was assumed to have melted in the following hour. The proposed equation to derive the "true" snowfall amount in the operational network for 1 h time periods is given in Table 3, Eq. (4). This simple equation can easily be implemented operationally and can improve the estimation of snowfall accumulation measured with the TPB. It is important to remember that analysis has

Table 3. Derived transfer functions in which each step adds a new variable. Top table is for 1 h period and bottom table is for 3 h period. The value of the coefficient of determination (R^2) increases with more variables and longer periods. The number of data points used in the analysis were 214 and 87, for 1 h period and 3 h period respectively. Equations (4) and (8) were used to correct the data as explained in Sect. 3.1. Variables: CR is catch ratio, T is temperature (° C), W is wind speed (m s^{-1}), Acc is accumulation (mm).

1 h transfer functions	
$\mathrm{CR} = 0.87 \times \exp(-0.198 \times W)$	$R^2 = 0.49$
$\mathrm{CR} = 1.01 \times \exp(0.077 \times T - 0.176W)$	$R^2 = 0.57$
$\mathrm{CR} = 0.925 \times \exp(0.069 \times T - 0.176 \times W + 0.078 \times \mathrm{Acc})$	$R^2 = 0.60$
True accumulation (1 h) = Acc/CR – 0.095 × Acc/CR + 0.095 × Acc (previous hour)	
3 h transfer functions	
$\mathrm{CR} = 0.84 \times \exp(-0.234 \times W)$	$R^2 = 0.52$
$\mathrm{CR} = 1.04 \times \exp(0.094 \times T - 0.201W)$	$R^2 = 0.60$
$\mathrm{CR} = 0.892 \times \exp(0.067 \times T - 0.212 \times W + 0.049 \times \mathrm{Acc})$	$R^2 = 0.65$
True accumulation (3 h) = Acc/CR	

shown that the error associated with this melting factor only accounts for, on average, less than 10 % of the true accumulation, and that the undercatch of precipitation due to other factors is the main source of error.

Following the same methodology, we considered snowfall during 3 h time periods, and only including events with a maximum temperature colder than 0 °C. As expected, the number of events for the analysis decreased from 214 to 87. The main goal was to try to determine whether reducing the error related to the melting delay in the funnel would produce a completely different relationship between the catch ratio and wind speed. As shown in Fig. 6, the catch ratio–wind speed relationships were similar for the 1 and 3 h accumulation periods. Also, as shown in Table 2 and Fig. 5, a reduction in the number of events with catch ratios greater than 1 for the 3 h accumulation period indicates that almost all the snow that fell in the funnel was melted and measured within the 3 h periods. These results demonstrate that using 1 h accumulation periods works well for operationally deriving an adjusted precipitation amount, but the adjustment was even better using 3 h accumulation periods (Table 3), as evidenced by the higher R^2 value for the with longer accumulation periods.

To estimate the uncertainty of the proposed equations we split the 1 and 3 h data sets each into two equal and independent data sets. One data set was used to calculate the regression equations (114 events for 1 h period, 45 events for 3 h period). The resulting equations were similar to those obtained using the entire data set. The accuracy of the resultant regressions was then independently evaluated using the second subsample of each data set (100 events for 1 h period, 42 events for 3 h period). For the 1 h data set the resultant RMSE was 0.13, and for the 3 h data set it was 0.11. These values are acceptable given that the R^2 were between 0.6 and 0.7, showing that there was still some residual uncertainty in the regressions due to the variability and complexity of the relationship between the measurements from a TPB and a weighing gauge within a DFIR.

3.2 Spatial distribution of the accuracy of snowfall measurements in Spain

After demonstrating the magnitude of TPB snowfall measurement errors and developing methodologies to address these errors, the areas within Spain where the impact of these adjustments will be most significant can be identified. Hereafter, we will use the units of km h^{-1} for wind speed because they are used in the operational network and can facilitate the comprehension of the results.

Figure 8 shows frequency distributions of 1 h average wind speeds during snowfall at sites in northern Spain. In the Cantabrian and Pyrenees ranges, most stations show that 60 % of the events occur during light winds or between 0 and 10 km h^{-1} (Fig. 8a), but for most of the stations in elevated areas of the plateau, less than 40 % of events occur at these light wind speeds. The percentage of snowfall events with wind speeds between 10 and 20 km h^{-1} (Fig. 8b) in the Cantabrian and Pyrenees ranges was less than 20 %. This increased to between 40 and 60 % for the other stations. Finally, the number of stations with a high percentage of snowfall events with wind speeds higher than 20 km h^{-1} (Fig. 8c) was very low (< 20 %), comprising only a few stations in the most elevated area of the Iberian range. The average wind speed at each station during snowfall events suggests the following trend: as the wind speed increases, the percentage with respect to the total number of snowfall events with these speeds decreases for stations located in the Pyrenees and the Cantabrian Range and increases for all other stations (Fig. 9).

Figure 10 shows the average temperature during snowfall events. The stations located in the Pyrenees and in some areas of the Iberian range are located at higher elevation and, for this reason, the temperature is on average lower during

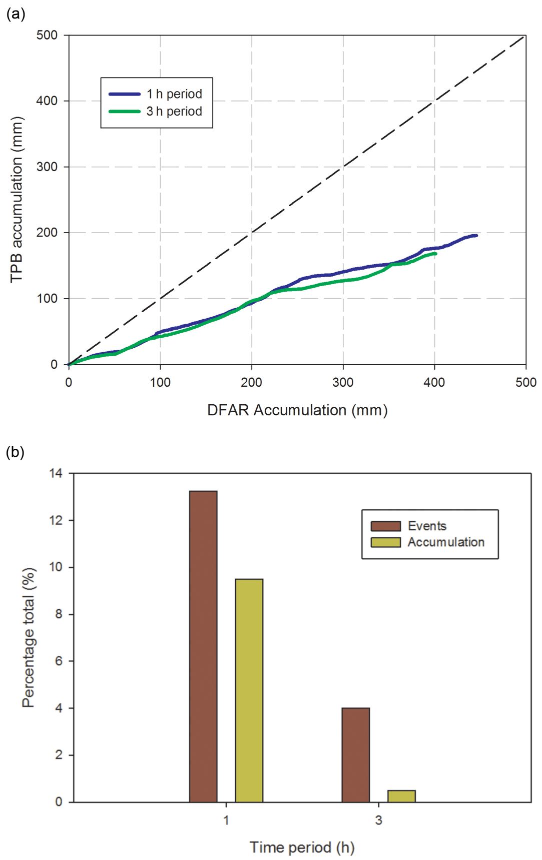

Figure 5. **(a)** Total accumulation reported by the TPB and DFAR and **(b)** percentage of events and accumulation during those events for which the catch ratio (TPB/DFAR) was greater than 1 for 1 and 3 h time intervals.

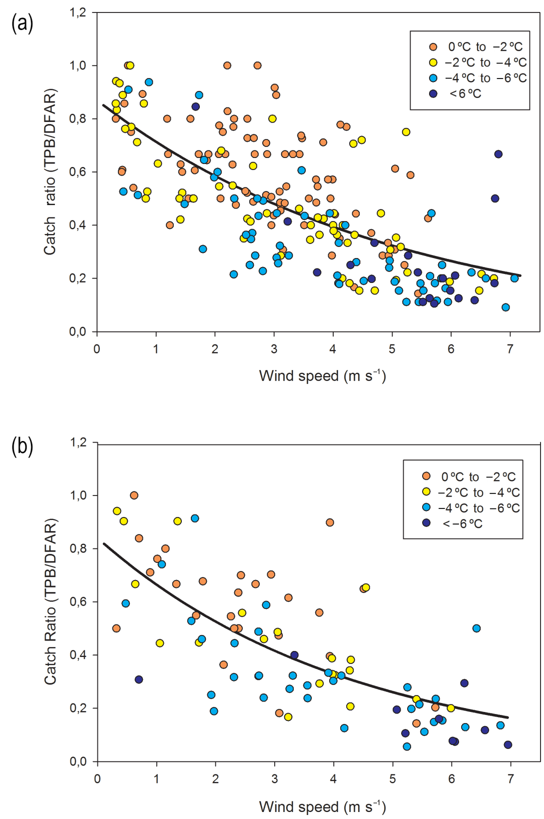

Figure 6. The relationship between catch ratio (TPB/DFAR) and wind speed for accumulation periods of **(a)** 1 and **(b)** 3 h. The mean temperature during each accumulation period is indicated by colour.

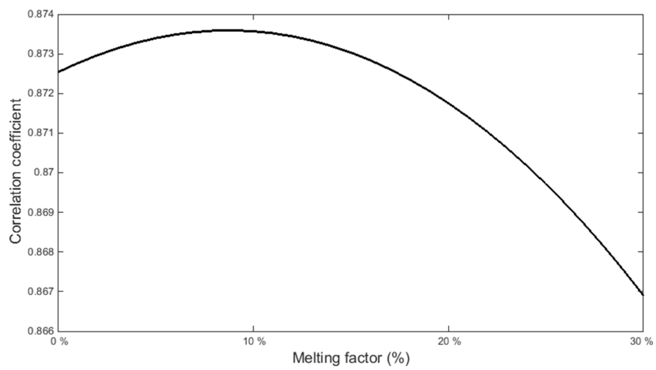

Figure 7. Correlation between the hourly TPB measurements and the DFAR measurements for different melting factors, where melting factor is the percentage of the Thies tipping bucket precipitation from a given hour melted in the following hour.

snowfall. As demonstrated previously in Sect. 3.1, the catch ratio decreases more rapidly with increasing wind speed at lower temperatures.

Using the derived transfer function (Eq. 2, Table 3), the average catch ratio for each station was calculated for all 1 h snowfall events (Fig. 11). The snowfall accumulation for stations located in the Pyrenees and Cantabrian ranges was underestimated by less than 50 %, whereas for stations located in the most elevated areas of the plateau and in the Iberian range, the underestimation ranged from 50 to 70 %. It is noteworthy that at stations characterized by light winds, the undercatch at sites with lower average temperatures was higher than that for stations with higher average temperatures. This was the case for some stations in the Pyrenees range in comparison with stations in the Cantabrian Range that are located at a lower elevation, and have more snowfall events at temperatures near 0 °C. In the easternmost area of the Iberian range, the lower temperatures in combination with high wind speeds produced the lowest catch ratios in Spain.

4 Discussion

The Formigal–Sarrios test site provided a unique opportunity to test the performance of the AEMET operational tipping bucket gauge as well as other gauges within the framework of the WMO-SPICE project (Buisan et al., 2016b; Nitu et al., 2015). The large number of snowfall events during the

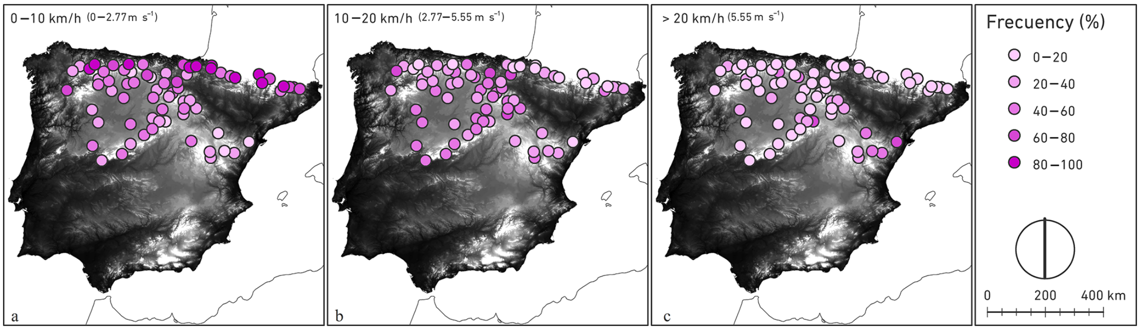

Figure 8. Percentage of 1 h snowfall events per station at different wind speed intervals.

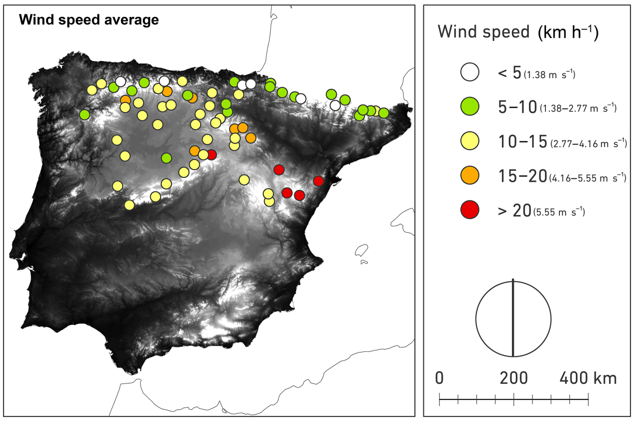

Figure 9. Average station wind speed during 1 h snowfall events.

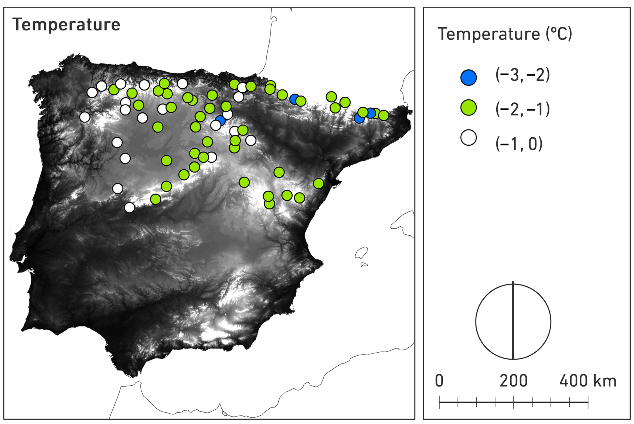

Figure 10. Average station temperature during 1 h snowfall events. The colours represent temperature ranges with different (minimum, maximum) temperatures as indicated in the legend.

2014/2015 winter season provided a data set encompassing a wide range of temperature and wind speed conditions. Intercomparison with the DFAR showed that in snow, the performance of the TPB was similar for accumulation periods of 1 and 3 h, with similar catch ratio relationships for both accumulation periods.

The main factor affecting the underestimation of precipitation was the wind speed, especially for cold events. At wind speeds below $4\,\mathrm{m\,s^{-1}}$, the catch ratio was as low as 0.4. At higher wind speeds, the catch ratio decreased dramatically to as low as 0.2 to 0.1 for wind speeds exceeding $7\,\mathrm{m\,s^{-1}}$. The impact of temperature and snowfall intensity on the catch ratio was less important than wind speed, but still noticeable, with temperature having a larger impact than intensity, especially under colder conditions. These results were consistent with the observed accumulation differences among gauges shown in the two snowfall time series in Fig. 3, for which losses in accumulation of 20 % for average wind speeds lower than $4\,\mathrm{m\,s^{-1}}$ (Fig. 3a) and of 60 % for average wind speeds close to $8\,\mathrm{m\,s^{-1}}$ (Fig. 3b) were evident. The main results of this study are also consistent with previous studies in which different gauges, including tipping buckets, were tested relative to the reference at different sites (Rasmussen et al., 2012; Wolff et al., 2014; Earle et al., 2016; Kochendorfer et al., 2017)

One factor that was not included in the analysis was the impact of heating on the evaporation or sublimation of incident precipitation producing losses in the TPB accumulation, especially at low intensities (Zweifel and Sevruk, 2002; Savina et al., 2012). The heating power of the model of tipping bucket used operationally and tested in Formigal was only 49 W (in comparison with other models of tipping bucket, which have different heating configurations, some with power greater than 100 W) and snowfall events at Formigal are usually characterized by high intensities. Based on this, we could consider that, in addition to the impact on catch efficiency already included in transfer functions, longer delays on the melting process could be expected. For this reason, the choice of 1 and 3 h time periods was considered a good option.

Despite the difficulty of discriminating rain from snow (Harder and Pomeroy, 2014), the upper threshold temperature of 0 °C was suitable for classifying the precipitation as snow. This was also supported by the high number of snow occurrences detected at temperatures warmer than 0 °C and its consistency with previous work (Fassnacht et al., 2013).

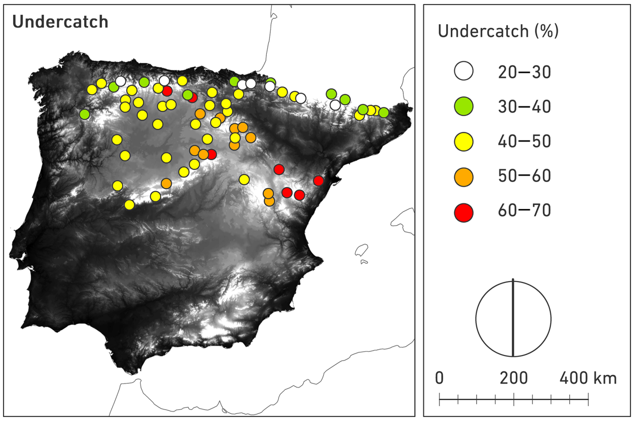

Figure 11. Average undercatch of precipitation for 1 h snowfall events at each station.

Wind speed was measured at the standard operational height of 10 m, instead of at gauge height. The main advantages are that measurements are less affected by obstacles, and that all stations in the operational network measure wind at this height. This allows for broader applicability of the derived transfer functions within the network. Previous work has shown only small improvements in the accuracy of results using the gauge height wind speed relative to using the 10 m wind speed (Kochendorfer et al., 2017).

From a national perspective, it is crucial to identify areas where the underestimation of precipitation can potentially have significant impact. A study of the climatic data set from the national archive for 2010 revealed two areas in northern Spain that exhibit different levels of underestimation during snowfall events. The Pyrenees and the north side of the Cantabrian Range were characterized by higher catch ratios than the elevated areas of the Iberian plateau. It therefore appears that the undercatch of snow was more significant at higher elevations (i.e. on the slopes). However, in terms of the total water equivalent that is not accounted for, it is likely the northern areas and the Pyrenees range experience more total undercatch because of the relatively large portion of winter precipitation occurring in these mountains as snowfall (Pons et al., 2010; Bootey et al., 2013; Buisan et al., 2014). It is also important to note that, in general, snowfall in Spain occurs very infrequently at temperatures colder than −3 °C, and the average 1 h wind speed during snowfall events is lower than 30 km h^{-1}. These limits fit quite well with the derived transfer functions, which cover temperatures between 0 and −8 °C and wind speeds between 0 and 30 km h^{-1}.

These adjustment functions will also help forecasters to infer, in near real time, the degree of danger during a snowfall event that could otherwise be significantly underestimated by the uncorrected TPB measurement. This in turn will result in more accurate warnings. An accurate assessment of the available snow water equivalent is critical to activate mechanisms to reduce the impact of the risk of floods associated with the rapid melting of snow at lower elevations (below 1500 m a.s.l.); for example, after a heavy snowfall event followed by an increase of temperature or rainfall episode. These results are therefore a first step forward in improving the precipitation input for hydrological models.

Within the Spanish climate record, winter precipitation is persistently underestimated, especially in areas subject to frequent snowfall (Pons et al., 2010; Buisan et al., 2014). This underestimation could affect previous studies of solid precipitation, especially if the period of time considered was associated with significant winter precipitation extremes (López-Moreno et al., 2011; Vicente-Serrano et al., 2011; Añel et al., 2014; Cortesi et al., 2014; Buisan et al., 2016a). Adjustment functions for the Hellman gauges (Goodison et al., 1998) traditionally used by AEMET and the transfer functions obtained in this study for the gauges used currently should be used to assess the actual precipitation trends in Spain.

This is the first study describing the underestimation of winter precipitation in Spain, and as such, it is a first step that has important applications in many different research (i.e. climatology, numerical modelling) and operational (i.e. nowcasting, hydrology) fields. Further research is needed, however, to obtain better corrections, to more accurately describe correction uncertainty using in situ validation and to define temperature thresholds that can be used to identify snowfall events for different locations. Preliminary tests of the transfer functions determined in this study were performed by the Spanish hydrological service. The response of hydrological models was significantly improved when initialized using the adjusted precipitation measurements.

Furthermore, the observed measurements of snow depth and liquid water equivalent recorded by observers in selected AEMET stations (i.e. Cubillo de Ebro, Cantabria; Mosqueruela, Teruel; Lalastra, Alava; and Sargentes de Lora, Burgos) during snowfall episodes agreed well with the derived precipitation when the transfer functions were applied. For example, based on manual snow depth measurements at the Lalastra station, the total liquid water equivalent for the 3–6 February 2015 blizzard was estimated to be between 150 and 250 mm. The gauge only measured 81.8 mm at this station, but after adjustment the corrected precipitation was 233.4 mm.

Finally, and perhaps most importantly, most countries use tipping buckets without shields in their operational networks (Nitu and Wong, 2010), and for this reason the underestimation of snowfall precipitation is a ubiquitous problem. The methodology presented here can be used by other national weather and hydrological services to test precipitation bias corrections and to identify regions where errors affecting snowfall accumulation are most significant.

5 Conclusions

The results of this study demonstrate that a transfer function between the Thies tipping bucket precipitation gauge and the SPICE reference can be derived for accumulated precipitation amounts over 1 and 3 h time intervals. Wind is the most dominant environmental variable affecting the gauge catch efficiency, especially at temperatures colder than −2 °C, at which the precipitation amount can be underestimated by up to 80 % of wind speeds higher than 5 m s^{-1}. Using archived data, it was inferred that, on average, snowfall accumulation in the Pyrenees and Cantabrian Range was underestimated by less than 50 %, whereas in the most elevated areas of the central plateau and in the Iberian range, the underestimation ranged from 50 to 70 %. These results can help operational forecasters, climatologists and hydrologists to estimate the degree of underestimation of precipitation amount under different weather conditions, and also to be aware of the areas of Spain where the underestimation is potentially higher.

Competing interests. The authors declare that they have no conflict of interest.

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