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Assessment of the underestimation of snowfall accumulation by tipping bucket gauges used operationally by the Spanish national weather service

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Abstract Within the framework of the WMO-SPICE (Solid Precipitation Intercomparison Experiment) at the Formigal-Sarrios test site located in the Pyrenees mountain range of Spain, the Thies tipping bucket precipitation gauge was assessed against the SPICE reference. 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 be 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 h 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 average catch ratio was 0.7. At 3 m s^{-1}, the average catch ratio was 0.5, and was even lower for temperatures below -2ºC and decreased to 0.2 or less for higher wind speeds. Following this, this study outlines two areas in Northern Spain that exhibit different catch ratios under weather conditions leading to snowfall events, highlighting the importance of how the precipitation gauge behaves in various conditions.

Keywords: WMO-SPICE, tipping bucket, solid precipitation, catch ratio, snowfall, Spain

1 Introduction

Accurate measurement of snowfall accumulation is critical because it strongly influences the ecological and hydrological response 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, 2008b, Uhlmann et al. 2009). Moreover, suitable snowfall warnings based on reliable real-time data must be issued by 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-induced updrafts 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 WMO Solid Precipitation Intercomparison (Goodison et al. 1992, 1998, Yang et al. 1995, 1998a, 1998b), 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. 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/CIMO multi-site intercomparison of instruments and systems of observation for the measurement of solid precipitation was initiated in 2012.

The focus of the WMO Solid Precipitation Intercomparison Experiment (WMO-SPICE) is on assessing the performance of different types of automatic precipitation gauges and configurations. WMO-SPICE has defined a reference configuration with a DFIR shield and automatic gauge in the center and 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) and more information about SPICE can be found at: http://www.wmo.int/pages/prog/www/IMOP/intercomparisons/SPICE/SPICE.html

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 2010, 2015, Lopez-Moreno et al. 2010, Cortesi et al 2014, Buisan et al. 2016, El-Kenawy et al. 2015). 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 now becomes 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 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 (AWS) 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 true snowfall amounts by this gauge is derived from the comparison against the DFAR. The wind speed during snowfall events is included 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 asl in the Pyrenees mountain range (Figure 1). This is a sub-alpine environment consisting of a mixture of bare ground and only very low grasses. The prevailing winds are from the northwest all year round. Snowfalls are frequent with maximum measured snow depths of almost 300 cm during the 2013-2014 and 2014-2015 winter seasons. Southerly and southwesterly snowfall events are associated with light winds and mild temperatures (near 0 °C) whereas northerly and northwesterly snowfalls are 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) inside a large double fence and referred to as the DFAR or R2 reference, and 2) as a shielded (single-Alter or SA) and unshielded (UN) pair and referred to as the R3 reference. A disdrometer (Laser Precipitation Monitor, Thies Clima, Göttingen, Germany) was also installed inside the DFAR. The tipping bucket (TPB) under test was a heated gauge (Precipitation Transmitter, Thies Clima, Göttingen, Germany) that is used in approximately the 80% of Automatic Weather Stations (AWS) in the AEMET operational network. The Pluvio2 output parameter used in this analysis was the “non real time” or NRT accumulations. The NRT output was used because of an integrated 0.2 mm per hour discrimination threshold which makes it more comparable to the Thies tipping bucket gauge whose minimum resolution is the same 0.2 mm. The output used from the Thies LPM disdrometer, which is also widely used in AEMET, included the intensity, total accumulation, precipitation type (the 1 minute METeorological Aerodrome Report or METAR code).

Figure 1 shows the site and the distribution of instruments in 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 a 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. The sampling frequency for each instrument was 1 minute and all the data were recorded using two Campbell CR1000 data loggers.

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 (1h and 3h) where less than 90% of the 1 minute data was available. All events considered as doubtful or erroneous were removed.

2.2 Features of AEMET Automatic Weather Stations operational network

The orography of northern Spain, the area where the probability of snowfall is higher, is quite complex in terms of elevation, with an elevated plateau in the center and numerous mountain ranges and basins surrounding the plateau (Figure 2). The northernmost part of northern Spain, within the Pyrenean range and the north side of Cantabrian range, is characterized by narrow valleys. This region is mountainous, with numerous peaks above 3000 m asl. Minor ranges such as the Iberian and Central 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 was retrieved from the national archive. All temperature, wind, relative humidity, and precipitation data from the AEMET network are sent daily to the National Climate Archive, where 10 min data are available from 2009 onward.

For the purpose of this analysis, snowfall events were defined as precipitation events that occurred when the average maximum temperature was below 0ºC and the total accumulation was greater than 0 mm during a 1 h time period.

Event selection was focused on data from Northern Spain from January 2010 until 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 Pyrenean range (Bootey et al. 2013, Buisan et al. 2014, Pons et al.2010). 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. Figure 3 a) shows a typical snowfall 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 3 b) shows that under colder temperatures and stronger winds (up to 10 m/s or 36 km/h) the differences in accumulation with the reference were significantly higher, with the TPB (65%), UN (60%) and SA (45%). In both situations, there is good agreement between both instruments DFAR and LPM which agree to within 90 - 100%. In both situations in Figure 3, the instruments performed as expected with a relatively good agreement in the timing of the accumulations. The deviations in accumulations are most likely related to the wind-induced undercatch related to each of the instrument configurations.

Figure 4 shows the number of cases classified by type of precipitation at 1 minute resolution as detected by the disdrometer during 2014-2015 winter season. Results showed that for precipitation events at temperatures below 0 ºC, snow is almost always detected with only traces of mixed precipitation. The number of cases where snow is detected above 0 ºC is still very high, which indicates that the threshold temperature of 0 ºC is suitable for classifying the precipitation as snow and not rain for the site. This was confirmed by in-situ observations from Formigal ski resort collaborators. This threshold seems to work well at this site but may not be suitable for other SPICE sites due to different climate regimes and elevation. The accumulated precipitation was calculated for the DFAR and tipping bucket for each 1 h period, providing that the average temperature was below 0 ºC 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 ratio of the TPB relative to the DFAR actually helps 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 detected less than a half of the actual amount of precipitation recorded 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 the TPB failed to detect 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 probably occurred mainly due to the delay in the melting of the snow caught by the TPB. For example, this delay can cause the TPB to report higher precipitation than the reference because the TPB may report snowfall for a 1 h period after the snowfall event as measured by the DFAR has ended. 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 it is melted in the next hour. However it is a low correction value in comparison with the differences due to 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 below 2 m/s the average 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 m/s. The decrease in catch ratio with wind speed 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 fit was performed to only snow events, and wind speed was found to explain more than 50% of the variance. However, as shown in Figure 6, at temperatures below -4 ºC and wind speeds above 4 ms^{-1} , this adjustment function slightly overestimates the catch ratio. For this reason, to derive a more accurate relationship of catch ratio versus wind, 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. To justify this, we performed a correlation between the hourly TPB measurements and the DFAR measurements (Figure 7). A peak in this correlation occurred when 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 in the operational network for 1 h time period is given in Table 3, Equation 4. This simple equation can be easily implemented operationally and can improve the estimation of snowfall accumulation measured with the TPB. It is important to remember that analysis has shown that the error associated with this melting factor only account for, on average, less than 10% of the true accumulation, and that the undercatch of precipitation due to other factor 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 below 0 ºC. As expected, the number of events for the analysis decreased from 214 to 87. The main goal was to try to determine if reducing the error related to the delay due to the melting in the funnel would produce a completely different relationship between the catch ratio and wind speed. As shown in Figure 6, the plot and the adjustment functions were similar for the 1 h and 3 h accumulation periods. Also, as shown in Table 2 and Figure 5, a reduction in the number of 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 without any delay. This result demonstrates that the approach of using the 1 h accumulation period works well for operationally deriving an adjusted precipitation amount, but the adjustment was even better using the 3 h accumulation period (Table 3), with the R^2 increasing with longer accumulation periods.

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. From this moment on we will use the units of km/h 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 Pyrenean ranges, most stations show that 60% of the events occur during light winds, or between 0 and 10 km /h (Figure 8a), but for most of the stations in elevated areas of the plateau less than 40% of the events occur at these light wind speeds. The number of stations with the percentage of snowfall events with wind speeds between 10 and 20 km/h (Figure 8b) in the Cantabrian and Pyrenean Range 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 wind speeds higher than 20 km/h (Figure 8c) during snowfall events 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 likewise confirms a clear spatial pattern: as the wind speed increases, the percentage with respect to the total snowfall events with these speeds decreases for stations located in the Pyrenes and Cantabrian Range, and increases for all other stations (Figure 9).

Figure 10 shows the average temperature during snowfall events. The stations located in the Pyrenees range and in some areas of the Iberian range are located at higher elevation, and for this reason the temperature, on average, is lower during snowfall, which as demonstrated previously can have a negative impact on catch ratio.

Using the derived transfer function (Equation 2, Table 3), the average catch ratio for each station was calculated for all snowfall events (Figure 11). The snowfall accumulation in stations located in the Pyrenees and Cantabrian range was underestimated by less than 50% whereas in 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 under-catch at sites with low temperatures was higher than at the warmer stations. 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 snowfalls events at temperatures near 0 ºC. 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 and conclusions

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. The large number of snowfall events during the 2014/2015 winter provided an excellent dataset encompassing a wide range of temperature and wind speed conditions.

Intercomparison with the DFAR showed that in snow the performance of the TPB is similar for accumulation periods of 1 h 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 lower speeds, below 4 m/s, the catch ratio was as low as 0.4. At higher speeds the catch ratio decreased dramatically to as low as 0.2 to 0.1 at wind speeds exceeding 7 m/s. The impact of temperature and snowfall intensity on the catch ratio was less important than wind speed but still noticeable, 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 Figure 3, where losses in accumulation of 20% for average wind speeds below 4 m/s (Figure 3a) and of 60% for average wind speeds close to 8 m/s (Figure 3b) were evident..

From a national perspective, it is crucial to identify the areas where the underestimation of precipitation can potentially have the highest impact. A study of the climatic dataset from the National Archive from 2010 revealed two areas in Northern Spain that exhibit different levels of underestimation during snowfall events. The Pyrenean and the north side of Cantabrian range where characterized by higher catch ratios than in the elevated areas of the Iberian plateau. However this was not necessarily because the wind speed was lower in these mountainous areas during snowfall events, as the measurement stations are generally located in the bottom of the valleys where they are less affected by the wind. As a result, the undercatch of snow was lower than it was 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 higher losses due to undercatch because of the relatively large portion of winter precipitation occurring in these mountains as snowfall (Bootey et al. 2013, Buisan et al. 2014, Pons et al.2010). It is also important to note that in general, except for some higher elevation stations above 1500 m asl, snowfall in Spain occurs below -3 °C very infrequently, and the average 1h wind speed during these episodes is lower than 30 km/h. These limits fit quite well with the derived transfer functions that range for temperatures between 0ºC and -8ºC and winds between 0 km/h and 30 km/h.

The results of this work can help to operational forecasters to be aware of the areas of Spain where the underestimation is potentially higher. These adjustment functions will also help forecasters 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 plan in advance and 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 asl) 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). Adjustment functions for the Hellman gauges (Godisson et al. 1998) traditionally used by AEMET and the transfer functions obtained in this study for the more recently used gauges 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 however is needed to obtain better corrections, more accurately describe correction uncertainty using in-situ validation, and also define temperature thresholds that can be used to determine snowfall for each individual location. However, preliminary tests performed by the Spanish hydrological service of the derived transfer functions significantly improved the response of hydrological models when initialized using the adjusted precipitation measurements. Also the observed measurements of snow depth and liquid water equivalent in selected AEMET stations during snowfall episodes agreed well with derived precipitation when the transfer functions were applied.

Finally, and probably 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.

Due to the AEMET commitment to the WMO-SPICE project all these activities are planned within the AEMET strategy, and the infrastructure installed in Formigal-Sarrios will be used as a long-term reference to monitor the changes in precipitation and test new instruments.

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Tables

Instrument (Manufacturer)	Configuration	Reference	Variable used	Acronyms
Weighing gauge Pluvio2 (OTT)	DFIR	R2	TNRT	DFAR
Disdrometer LaserPM (Thies)	DFIR	R2	Intensity total precipitation	LPM
Weighing gauge Pluvio2 (OTT)	Single alter	R3	TNRT	SA
Weighing gauge Pluvio2 (OTT)	Unshielded	R3	TNRT	UN
Tipping Bucket (Thies)	Unshielded	AEMET Network	Standard	TPB

Table 1 List of instruments under test at the Formigal-Sarrios WMO-SPICE site.

DFAR/TPB	YES	NO
YES	238 (400.33 mm)	11 (2.6 mm)
NO	156 (45.11 mm)	

DFAR/TPB	YES	NO
YES	96 (385.58 mm)	6 (1.6 mm)
NO	41 (15.62 mm)	

Table 2: Contingency tables of cases detected by each instrument and the sum of accumulation not detected for 1 h and 3 h accumulation periods. In the YES/YES case the precipitation amount is that measured by the reference.

1h Transfer functions	
(1) CR=0.87*exp(-0.198*W)	R^2=0.49
(2) CR=1.01*exp(0.077*T-0.176W)	R^2=0.57
(3) CR=0.925*exp(0.069*T-0.176*W+0.078*Acc)	R^2=0.60
(4) True accumulation (1h)= Acc/CR – 0.095*Acc/CR+ 0.095*Acc(previous hour)	
3h Transfer functions	
(5) CR=0.84*exp(-0.234*W)	R^2=0.52
(6) CR=1.04*exp(0.094*T-0.201W)	R^2=0.60
(7) CR=0.892*exp(0.067*T-0.212*W+0.049*Acc)	R^2=0.65
(8) True accumulation (3h) = Acc/CR	

Table 3 Transfer Functions. CR=Catch Ratio, T=Temperature (°C), W=Wind speed (m/s), Acc=Accumulation (mm)

Figures

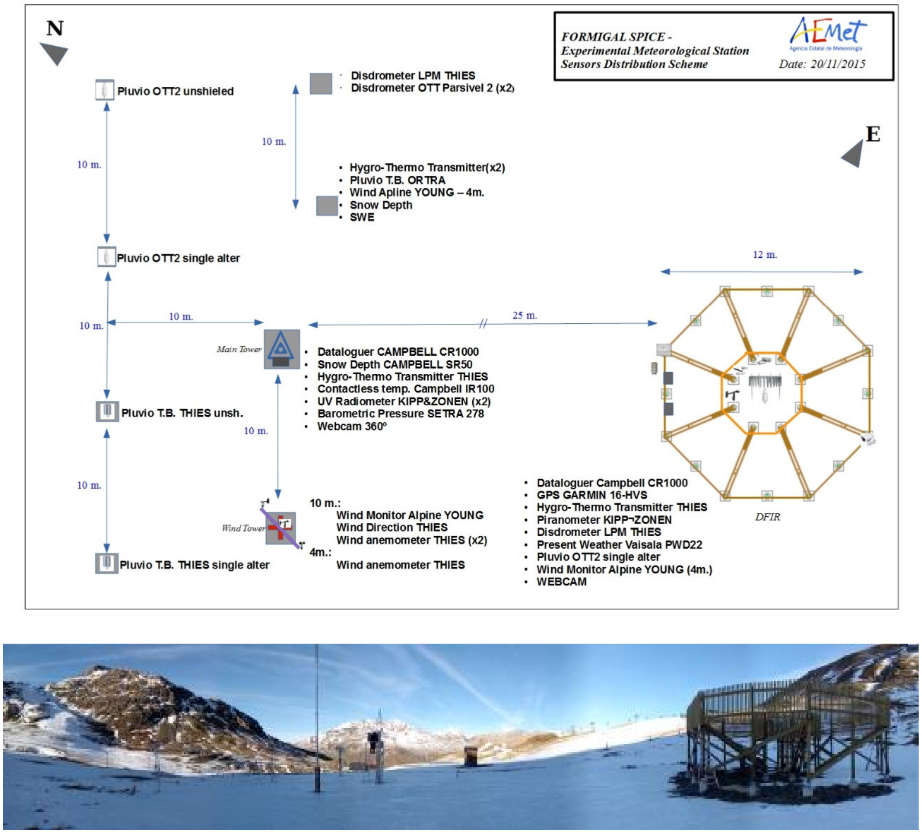

Figure 1 Layout and photograph of the Formigal-Sarrios test site

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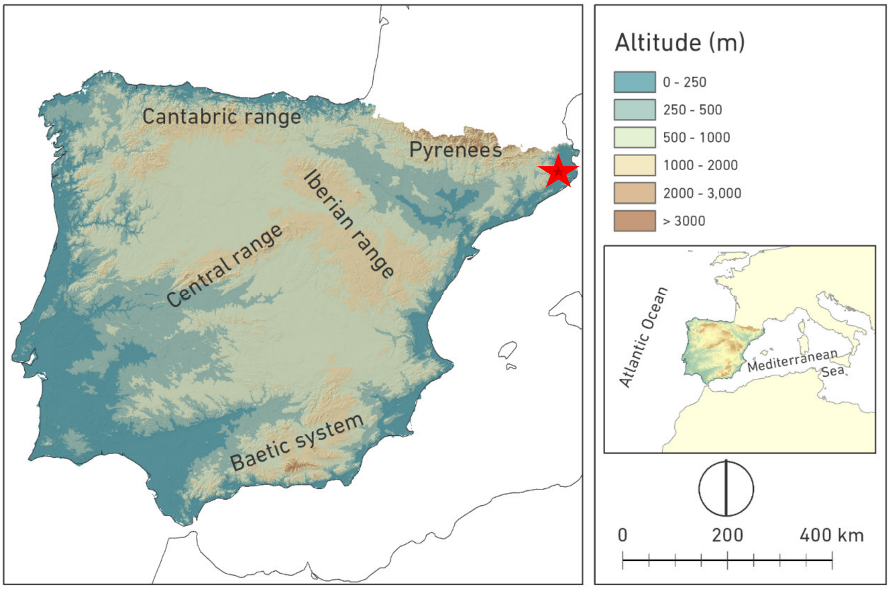

Figure 2. Orography of Spain and location of Formigal-Sarrios site

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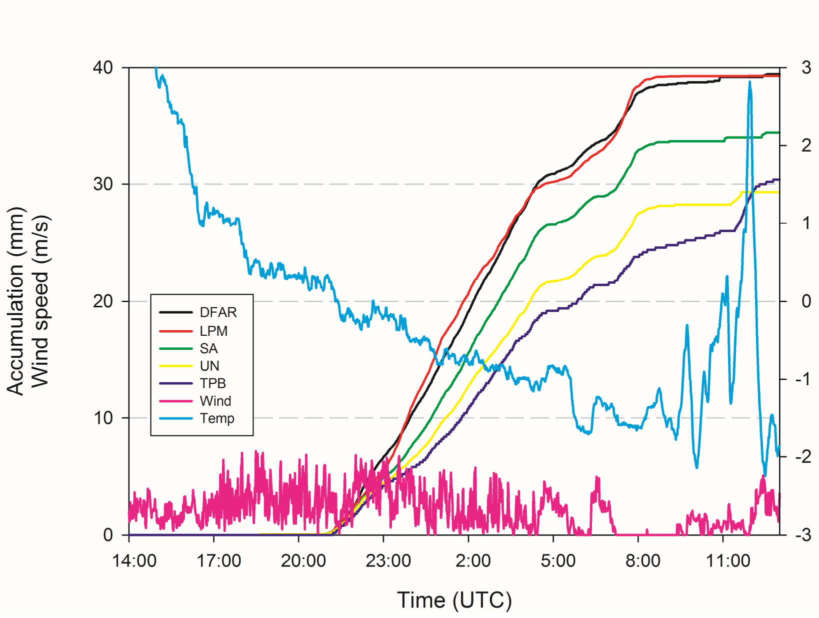
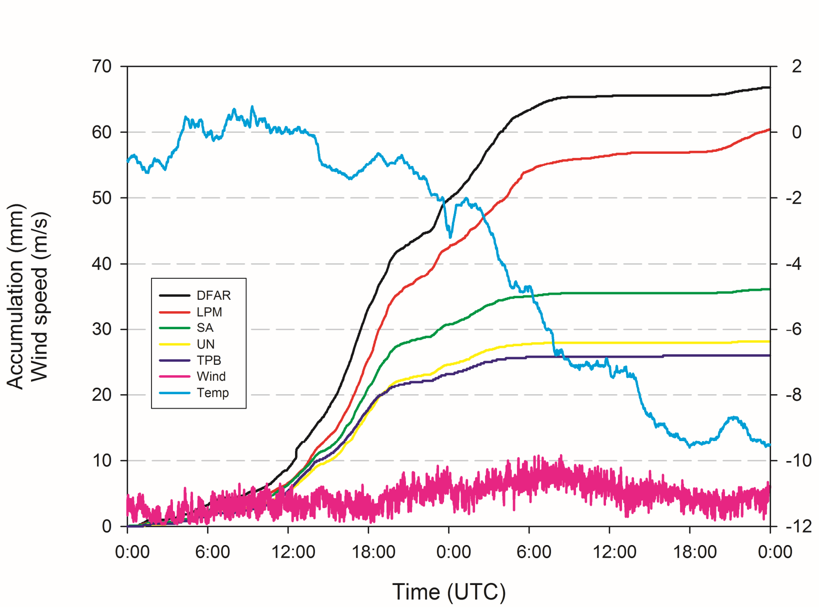


a)



b)

Figure 3 Episodes of snowfall accumulation a) 16-17 January 2015 b) 26 – 28 December 2014

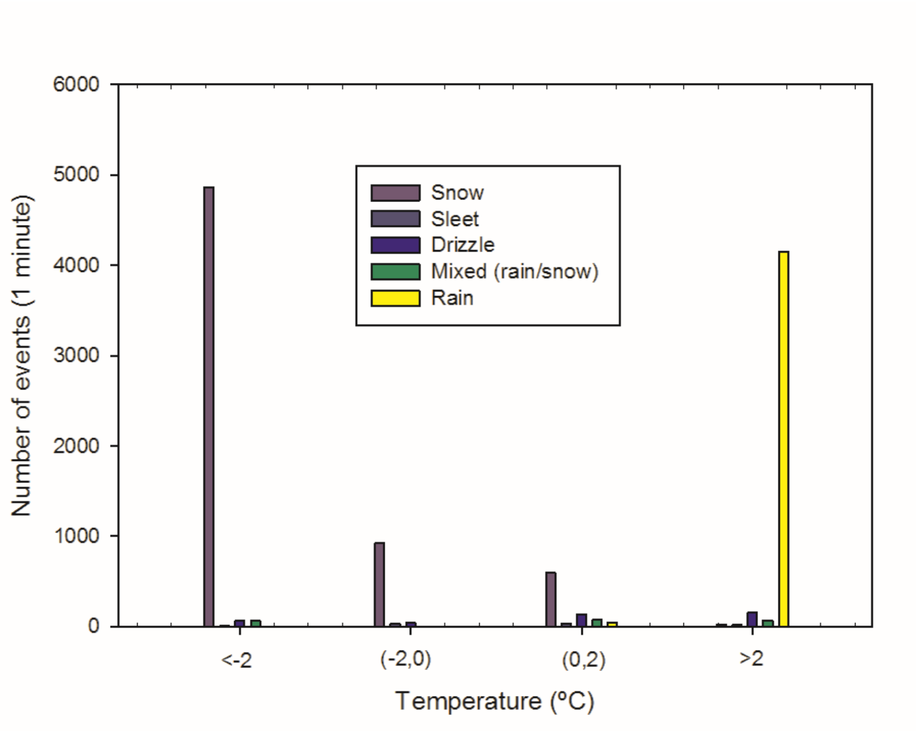
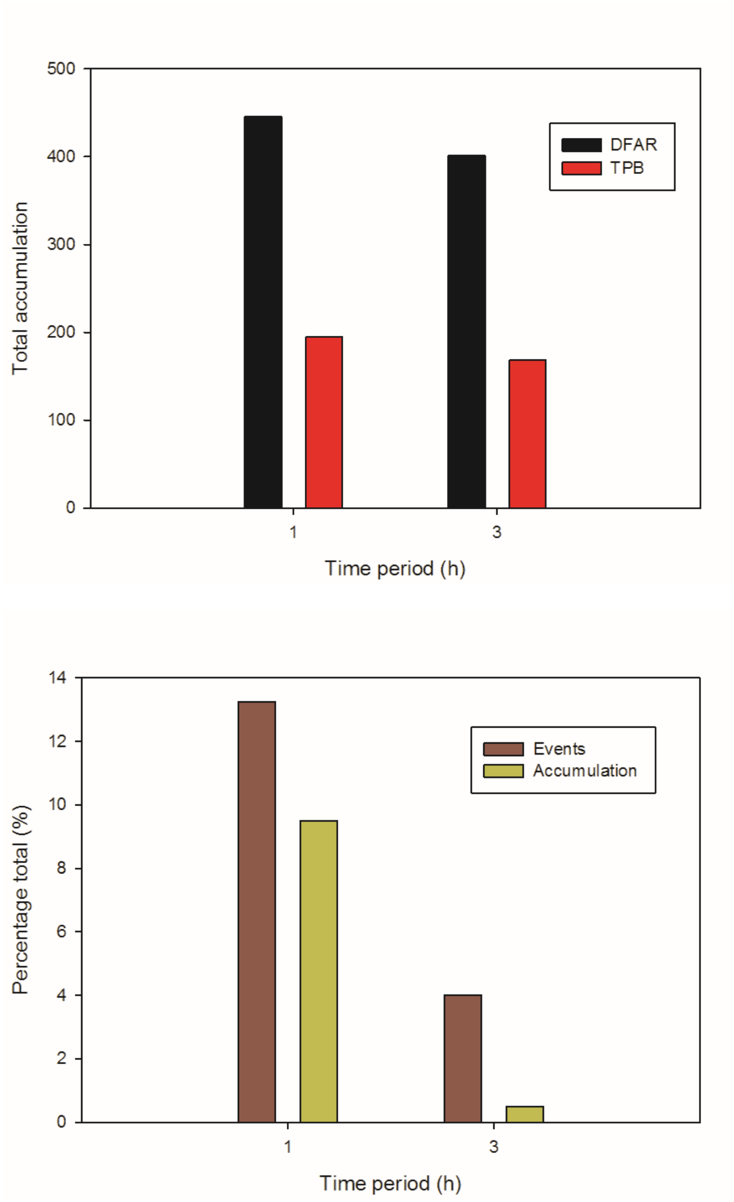


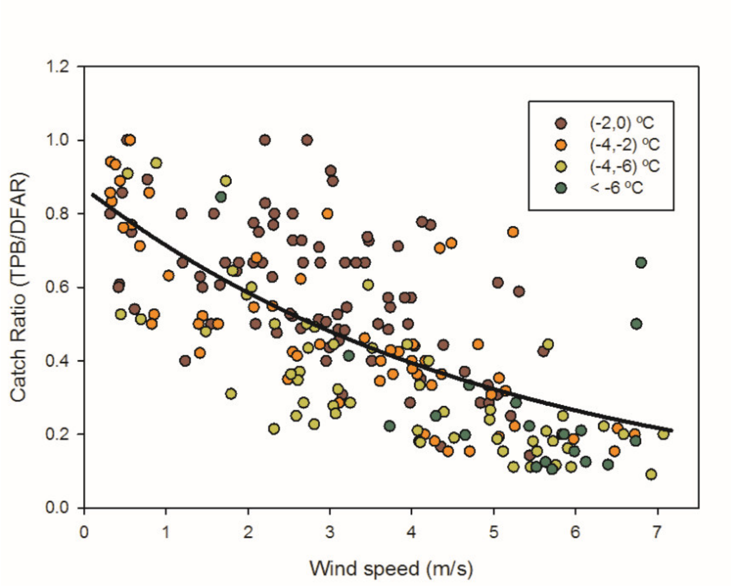
Figure 4 **Frequency distribution of precipitation type binned by temperature using 1-minute data derived from the disdrometer**



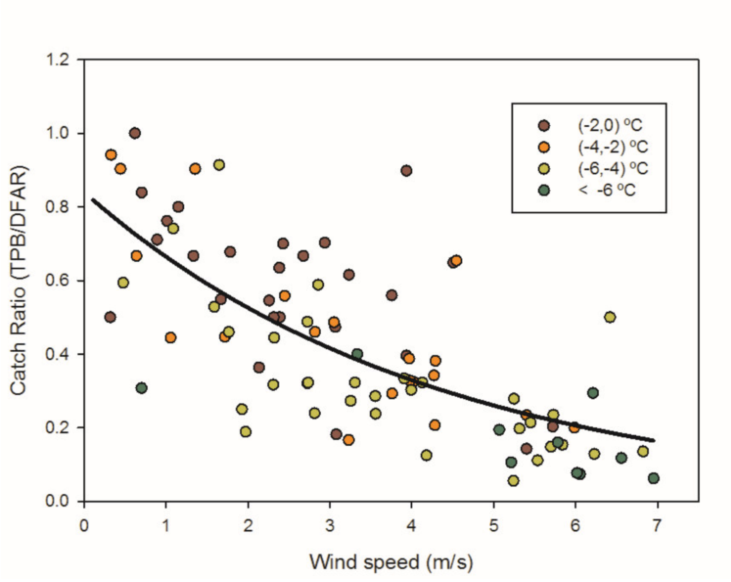
a)

b)

Figure 5 Differences between DFAR and TPB for accumulation periods of 1 h and 3 h for a) total accumulation and b) percentage of events and accumulation during those events where the catch ratio (TPB/DFAR) was greater than 1



a)



b)

Figure 6 The relationship between catch ratio (TPB/DFAR) and wind speed for different accumulation periods of a) 1 h and b) 3 h

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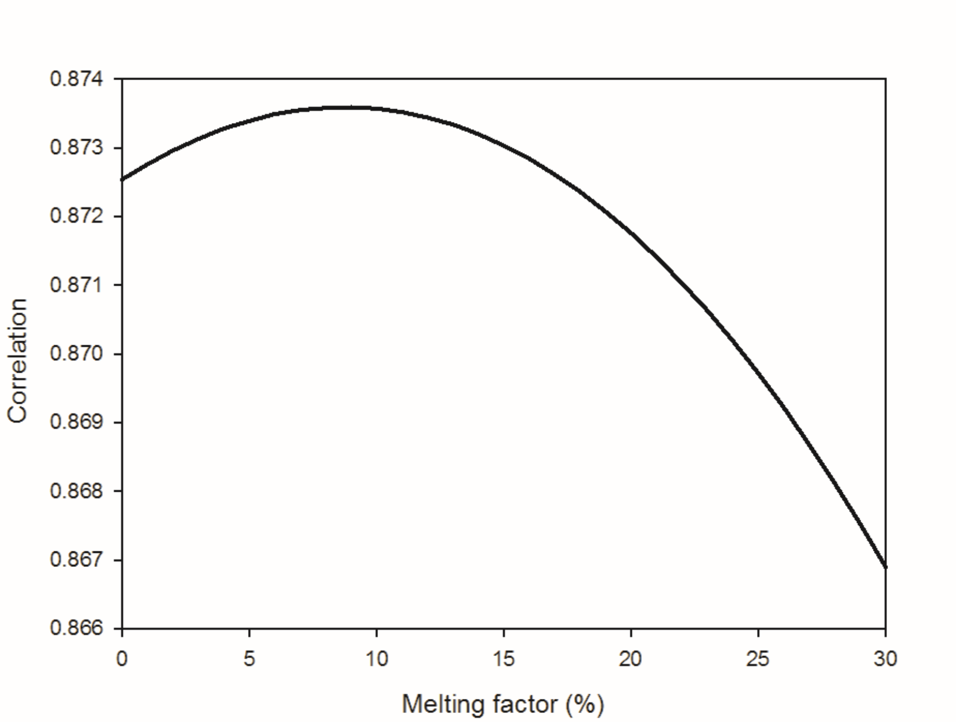

Figure 7 Correlation between the hourly TPB measurements and the DFAR measurements for different melting factors

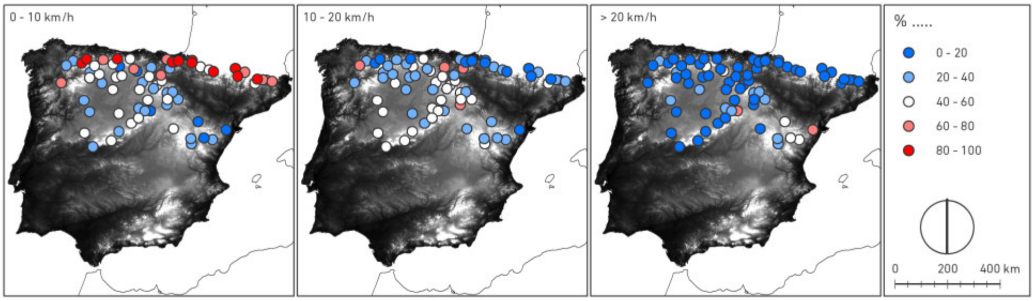

Figure 8 Percentage of 1 h snowfalls events per station at different wind speeds intervals

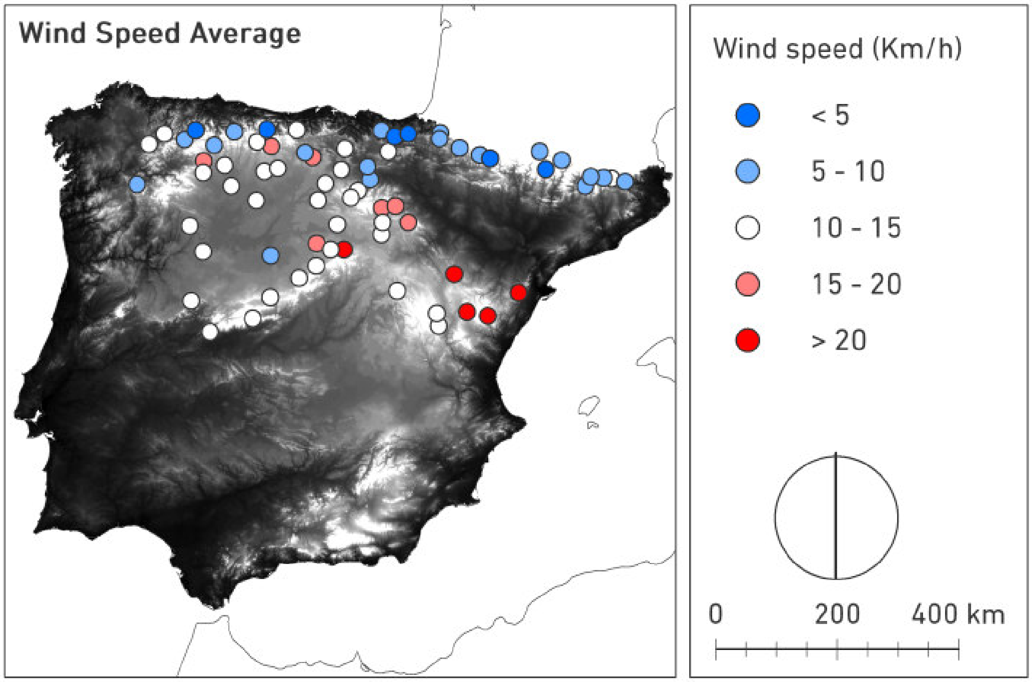

Fig 9 Average station wind speed during snowfalls events

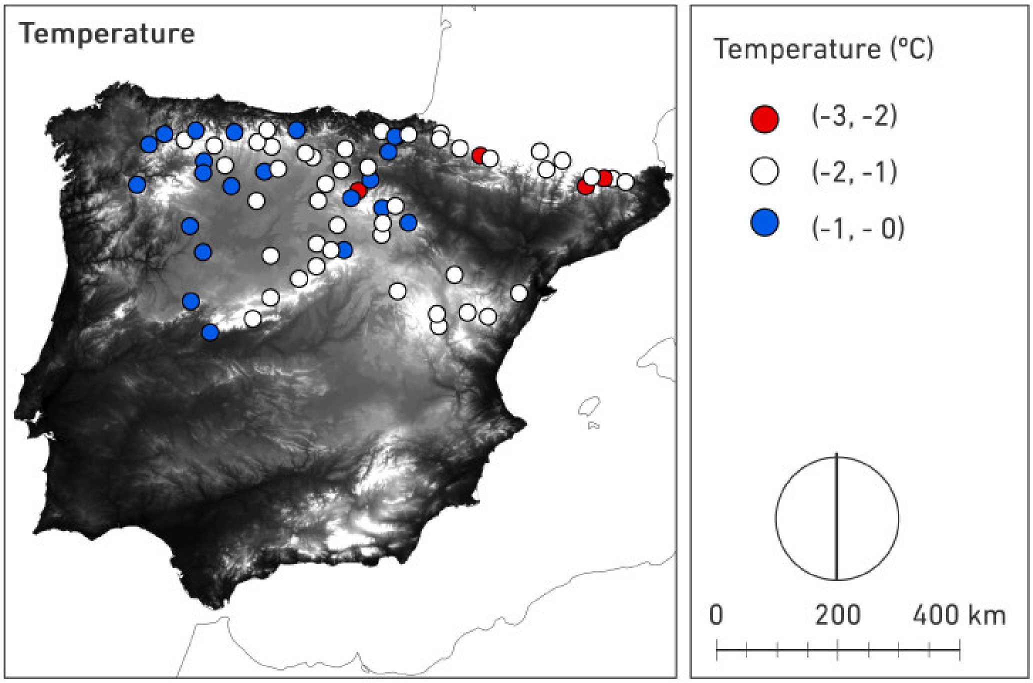

Fig 10 Average station temperature for snowfalls events

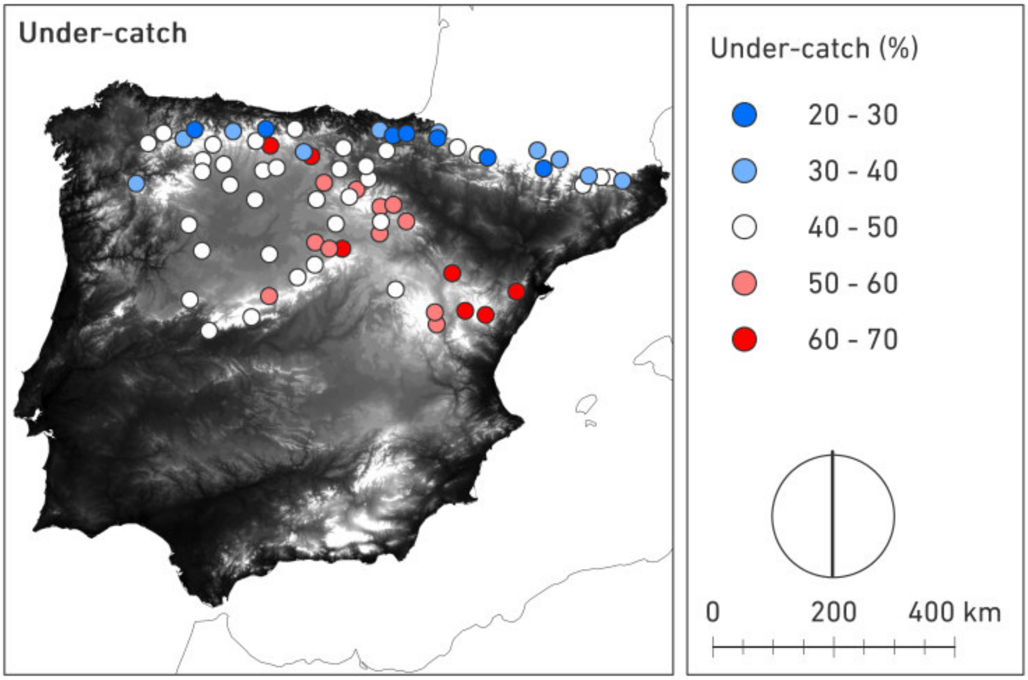

Fig 11 Average station under-catch of precipitation for snowfalls events