BAMS Map Room

# Adjustment of Solid Precipitation during the Filomena Extreme Snowfall Event in Spain

## From Observations to "True Precipitation"

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**ABSTRACT:** On January 2021, the heaviest snowfall in five decades hit central Spain, especially affecting Madrid. The city's Barajas International Airport closed, along with a number of roads, and all trains to and from Madrid were cancelled. This storm was named Filomena by the Spanish Meteorological Agency (AEMET), and produced continuous snowfall in Spain on 7–10 January. The observed snow depth was around 50 cm in 24 h in Madrid, and even higher in other areas of Spain. However, the measured accumulation of national precipitation gauges was not consistent with the observed accumulated snow on the ground and with the modeled weather forecast. The undercatch of solid precipitation was the primary reason for this inconsistency. This undercatch was quantified using transfer functions developed from the World Meteorological Organization (WMO) Solid Precipitation Intercomparison Experiment (SPICE). Results show that an underestimation of 20%–30% of solid precipitation in large areas of Spain was observed, with some areas experiencing even larger differences. Without adjustments, it was impossible to accurately validate the model forecast. The adjusted precipitation was also more realistically distributed, and it was more consistent with all the damage that occurred. The same methods can be applied to other snowfall events occurring anywhere in the world, and also using different precipitation gauges and/or models. This an example of the type of extreme events that modelers, forecasters, and climatologists should be aware of to avoid misinterpreting differences between modeled precipitation, observed precipitation, and nowcasting.

**KEYWORDS:** Snowfall; Gauges; Automatic weather stations; Nowcasting; Numerical weather prediction/forecasting

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Snowfall is one of the most difficult meteorological variables to measure using automated sensors (Goodison et al. 1998; Rasmussen et al. 2012; Nitu et al. 2018; Kochendorfer et al. 2022). Solid precipitation (precipitation in the form of snow) measurements are subject to large errors, due primarily to undercatch caused by wind. These errors may impede the improvement of precipitation forecasts, with implications for climate, model verification, data assimilation, and nowcasting.

In nowcasting, precipitation forecasts made by numerical weather prediction (NWP) models are typically verified using precipitation gauge observations that are prone to the wind-induced undercatch of solid precipitation. Therefore, apparent model biases in solid precipitation forecasts may be due in part to the measurements and not the model (Wang et al. 2019; Køltzow et al. 2019, 2020; Buisán et al. 2020).

Extreme snowfall events in regions where snow is rare disrupt transport, increase the number of traffic accidents and injuries, and affect the normal function of infrastructure in inhabited areas. For these reasons, the accurate measurement of the liquid equivalent amount of solid precipitation associated with such events is critical for assessing the impact of extreme events. To improve the accuracy of solid precipitation measurements and to help validate forecasted precipitation, precipitation measurements can be adjusted using transfer functions designed to minimize the effects of undercatch caused by wind speed (Wolff et al. 2015; Kochendorfer et al. 2017, 2020; Buisán et al. 2017; Colli et al. 2020).

In January 2021, the heaviest snowfall in five decades hit central Spain, especially affecting Madrid. The city's Barajas International Airport closed, along with a number of roads, and all trains to and from Madrid were cancelled. Figure 1 shows some images of the observed snow on the ground. This storm was named Filomena by the Spanish Meteorological Agency (AEMET), and produced continuous snowfall in Spain on 7–10 January. The observed accumulated snow depth on the ground was around 50 cm in 24 h in Madrid, and even higher

**Fig. 1. (left) Barajas Airport, (center) 50 cm of snow depth measurement at Madrid, and (right) Madrid buried in snow. Images courtesy of (left) Spanish National Meteorological Agency (AEMET) and José Antonio Quirantes (@JoseAQuirantes).**

in other areas of Spain. However, the accumulation measured by national precipitation gauges was not consistent with the observed accumulated snow on the ground.

The undercatch of solid precipitation was the primary reason for this inconsistency. Using transfer functions developed from the WMO SPICE project (Nitu et al. 2018), this undercatch was quantified. The objective was to assess the magnitude of the precipitation that was not accounted for, and to derive a more accurate estimate of precipitation that better explains the magnitude of the event, allowing a more accurate comparison with the model forecast.

## Methods

Stations equipped with unshielded tipping-bucket-type gauges from the AEMET operational network were used to calculate the spatial distribution of precipitation during the event. Quality control of the data was performed by excluding stations with unheated tipping-bucket gauges and stations with measurement gaps and data inconsistencies when compared with surrounding stations (i.e., delays on melting solid precipitation or no measured precipitation during the event). After this procedure 544 stations were selected. Figure 2 shows the spatial distribution of stations and the orography of Spain. There is an elevated plateau in the center of Spain, where Madrid is located, with numerous mountain ranges and basins surrounding the plateau. The many elevation changes in a relatively small area impact the synoptic meteorology and the surface temperature, which both affect the precipitation phase.

Two possible transfer functions are available for use with these unshielded heated tipping-bucket precipitation gauge measurements, that from Kochendorfer et al. (2020) and that from Buisán et al. (2017). The main differences are that those from Kochendorfer et al. (2020) were developed including data from different types of tipping buckets and also cover the adjustment for temperatures above 0°C, whereas those from Buisán were more focused on an single type of tipping bucket (the Thies tipping bucket with a heating power of 49 W and 0.2-mm resolution) and are also more conservative in terms of precipitation type because only adjustments for temperature below 0°C were developed.

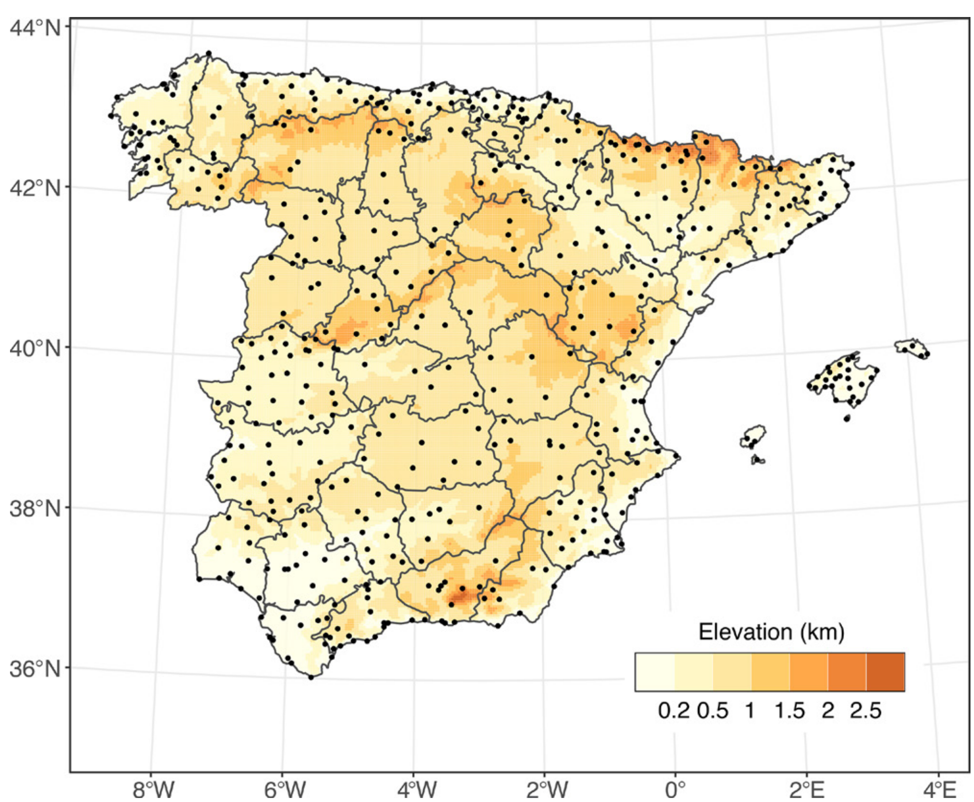


**Fig. 2. Spatial distribution of stations in each Spain province. Shading shows the orography of Spain.**

Although approximately 80% of the AEMET stations use the same precipitation gauge (the Thies tipping bucket), there are other types of tipping-bucket gauges in the Spanish National network (i.e., from MetOne or even Thies, but with different resolution and power). Regarding dynamical characteristics of gauge body all of them had the same shape (cylindrical) and same orifice size (200 $cm^2$), which guarantee also more consistency on the measurements. (Cauteruccio et al. 2021).

This was the first reason to adjust the precipitation using the transfer functions developed by Kochendorfer et al. (2020) instead of those of Buisán et al. (2017). The second reason was that snow was clearly observed at temperatures above 0°C, based on METAR and SYNOPS reports from airports and main stations within the affected area.

The form of the transfer function used in this work is the following:

$$\mathrm{CE} = ae^{-bU},$$

where CE is the catch efficiency for a 1-h period, $U$ is the hourly average wind speed at a height of 10 m, and $a$ and $b$ are the coefficients that depend on the average hourly temperature:

$$a = 0.722, b = 0.0354 \quad 2^\circ \geq T \geq -2^\circ\mathrm{C}\left(\text{Mixed precipitation}\right),$$

$$a = 0.7116, b = 0.1925 \quad T < -2^\circ\mathrm{C}\left(\text{Solid precipitation}\right).$$

To calculate and compare the accumulated model precipitation we used the sum of accumulated precipitation of the operational high-resolution European Centre for Medium-Range Weather Forecasts (ECMWF) Atmospheric Model for each day from base time 0000 UTC and day + 1 precipitation forecast for the next 24 h. The grid resolution to calculate the spatial distribution of precipitation was 0.1°.

## Results

To demonstrate the magnitude of the snowfall, Fig. 3 shows the adjusted precipitation at Barajas International Airport. During the snowfall event the mean temperature was −0.46°C and the average wind speed was 4.4 m $s^{-1}$. The accumulated precipitation indicates continuous snowfall for more than 24 h, with an increase of wind speed during the period of higher precipitation, which caused increased undercatch. The final measured accumulation was almost 38.2 mm; however, after adjustment the final accumulation was 60.9 mm, resulting in an undercatch of 38%. The resultant adjusted precipitation is more consistent with the observed snow on the ground and with the estimated densities of fresh snow, with values higher than 100 kg $m^{-3}$, which implies that 1 mm of solid precipitation results in less than 1 cm of snow accumulated on the ground.

A large area of Spain experienced similar weather conditions (Fig. 4), with the storm moving slowly from the south to central and northeast Spain as an extratropical structure (cold, warm, and occluded fronts). Meanwhile, a very cold polar air mass with minimums below 0°C was established over nearly the entire Iberian Peninsula. When the storm reached the peninsula, the warm and humid air moved over the very cold air. With the exception of some southern coastal areas, all precipitation occurred as snow, especially in a band of precipitation crossing central Spain from southwest to northeast. Severe weather warnings were declared in most of those areas due to the high 24-h precipitation accumulations in the form of snow.

Figure 5 shows the measured and adjusted spatial distribution of precipitation during the event. The storm affected mainly south, central, east, and northeast Spain. The highest

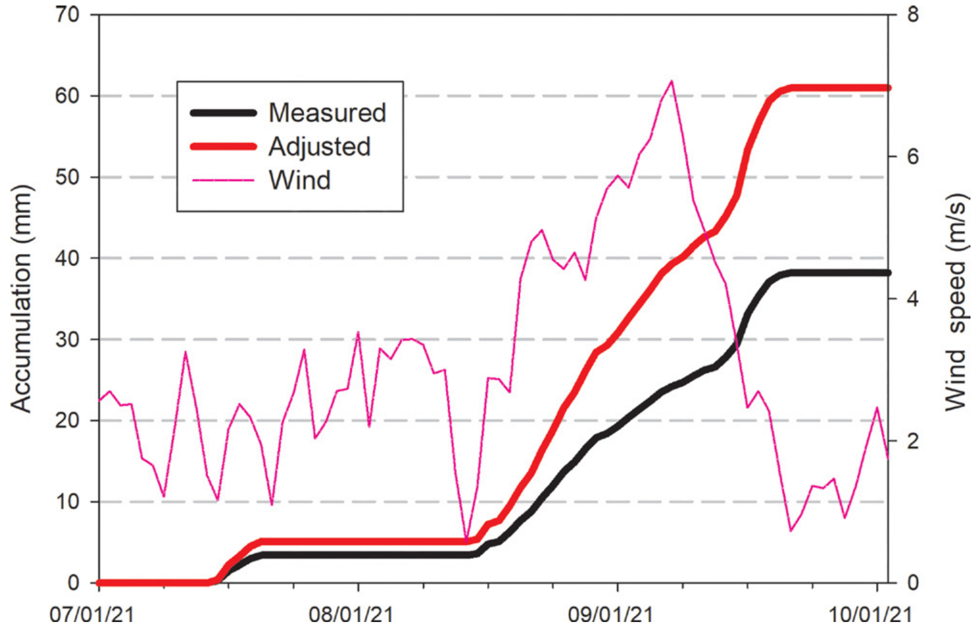


**Fig. 3. Average hourly wind speed at 10-m height and measured and adjusted precipitation at the main observatory in Barajas Airport, where 50 cm of snow depth were reported.**

precipitation accumulations were observed in the south and east of Spain and at these locations all precipitation was in liquid form and no undercatch was observed. However, on the central plateau all the precipitation was in solid form and the measured precipitation was below 30–40 mm. The same pattern was also observed even at northeast locations, far from the central plateau, where elevations are lower, and where the precipitation was mixed, solid and liquid. However, when transfer functions were applied, the distribution of precipitation was more consistent, with large areas of the central plateau and surrounding mountainous areas with adjusted precipitation well above 50–60 mm.

The differences between measured and adjusted precipitation measurements were influenced by several factors, such as changes in elevation producing a higher probability of solid precipitation and colder temperatures, topographic features that are related with windier environments during snow events, and the behavior and movement of Filomena affecting some areas of Spain differently.

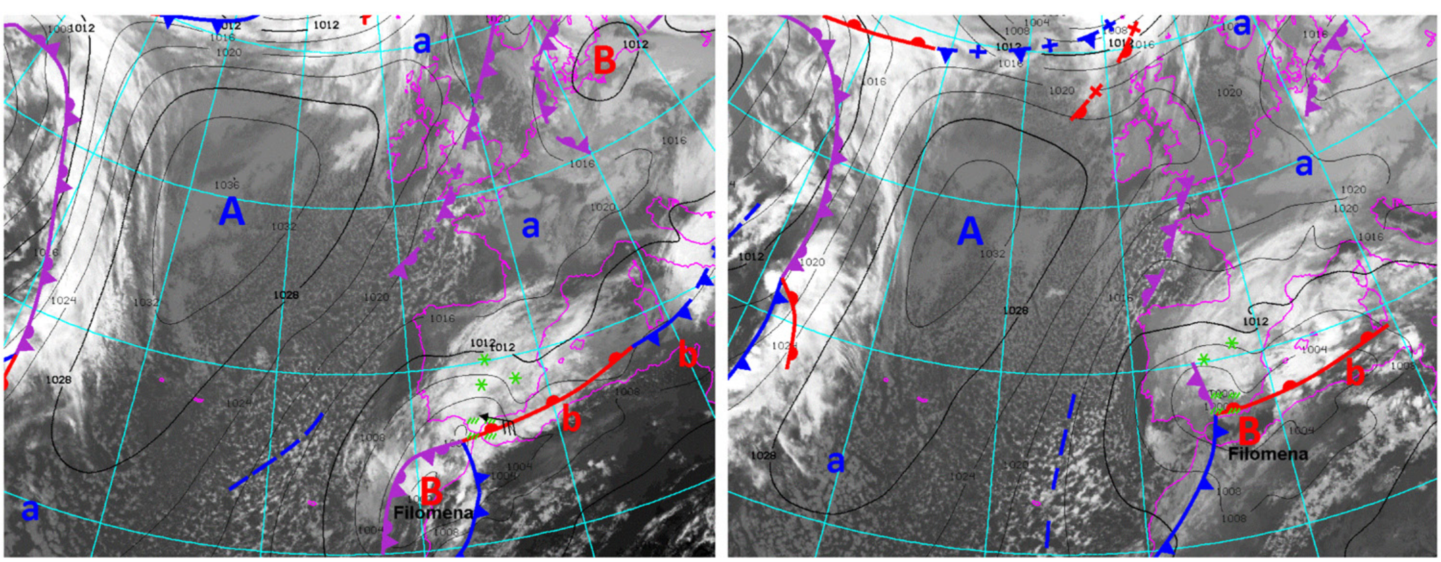


**Fig. 4. Infrared satellite images and surface analysis at (left) 0000 UTC 8 Jan and (right) 0000 UTC 9 Jan.**

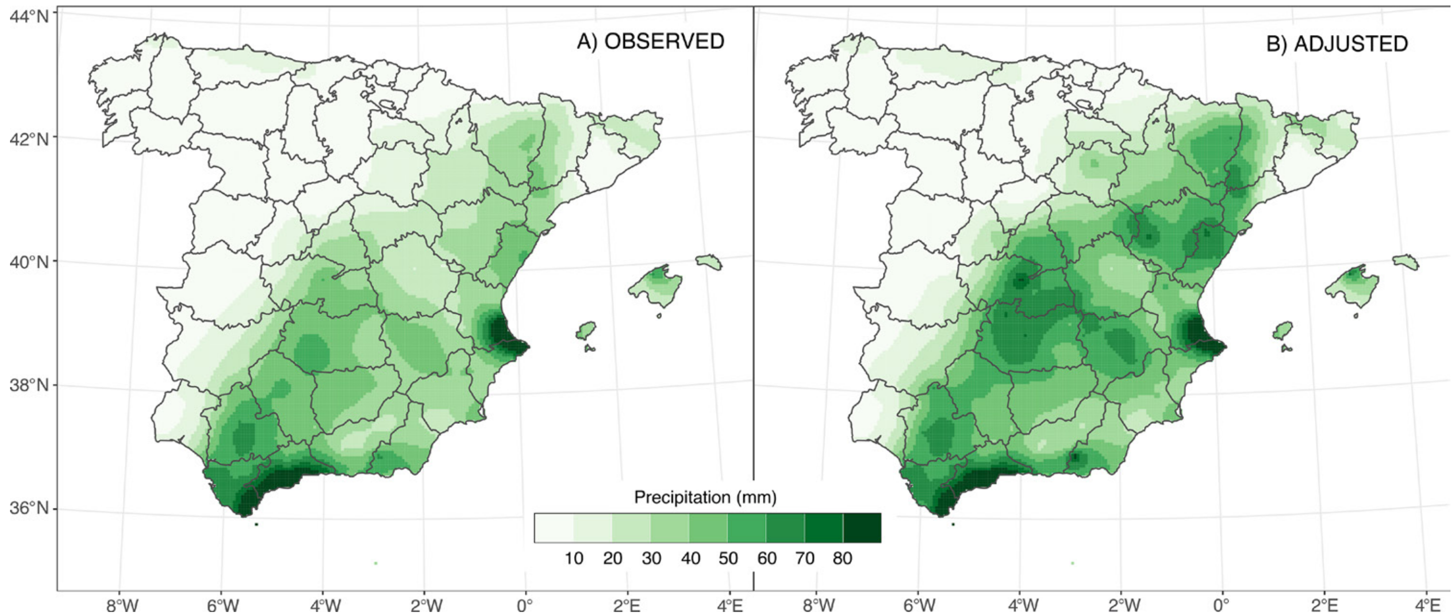


**Fig. 5. (a) Observed and (b) adjusted spatial distribution of precipitation (mm).**

Figure 6a shows that, after the adjustment, in many areas differences of about 25 mm occurred, with maximum differences greater than 35 mm. It is important to emphasize that this result does not necessarily show the areas where more precipitation was observed, but areas where the undercatch was higher in terms of total precipitation in millimeters. The main causes of these largest differences were due to a combination of factors. A high proportion of solid precipitation and colder temperatures (occurring mostly at higher elevations) increased the probability of dry and light snow. Locations with significant undercatch were also typically on elevated unforested plateaus, which were more exposed to the wind.

Figure 7 shows a photo of a station (Bello, Teruel, 1,006 m MSL) taken 13 days after the event. This station experienced one of the highest differences in solid precipitation after adjustment (50 mm), with Filomena depositing a depth of about 75 cm of snow on the ground. This area is characterized by the conditions described above: high precipitation, cold temperatures, and windy conditions. The adjustment for this location helped reconcile the

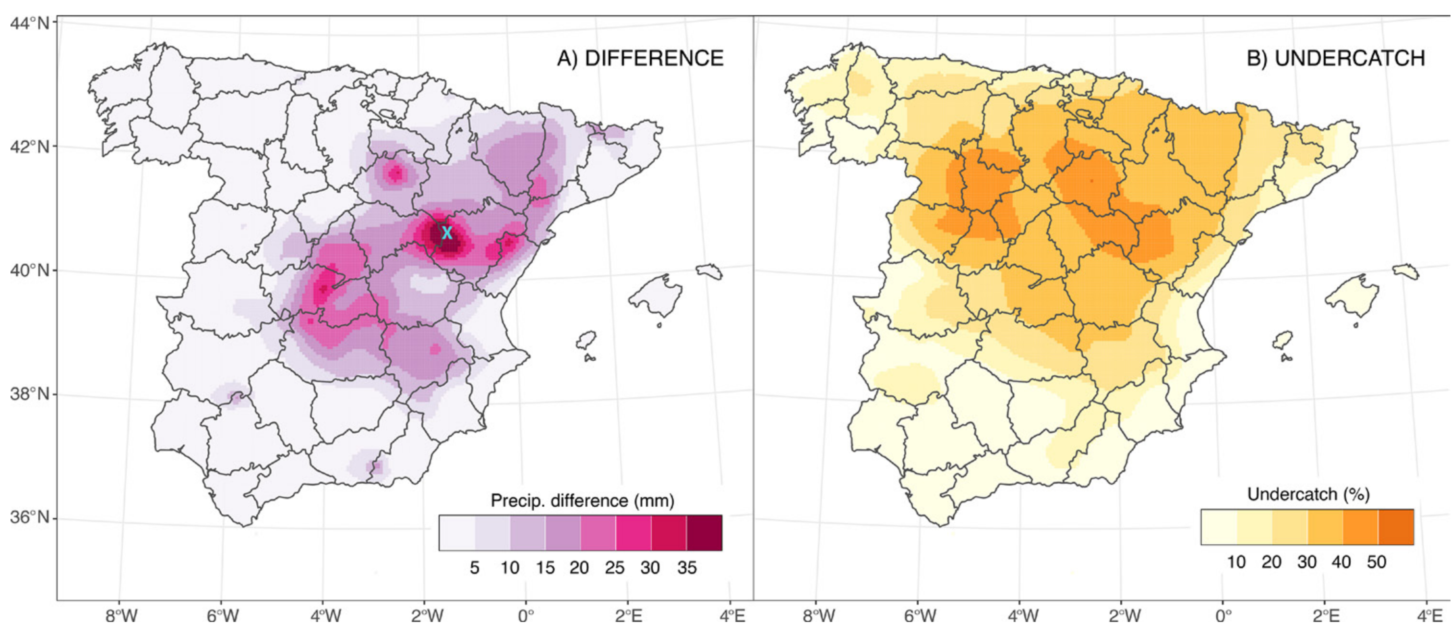


**Fig. 6. (a) Differences between measured and adjusted precipitation (mm; the blue cross shows location of the Bello automatic weather station) and (b) undercatch (%) of precipitation.**

observed differences between the snow depth and solid precipitation measurements.

Fig. 7. Partial view of the Bello automatic weather station on 21 Jan where still 30 cm of snow depth was observed.

Figure 6b shows that northern areas of the central plateau experienced higher relative undercatch, with values of around 40%. This result is consistent with the findings of Buisán et al. (2017), which showed that in these areas of Spain the percent undercatch is typically high during snowfall. However as total precipitation was generally low in western Spain, the total precipitation missed in this area was low (<5 mm) in comparison to central and eastern areas. This demonstrates that areas of high relative undercatch often do not coincide with areas where the largest amount of total precipitation are missed.

Figure 8a shows the differences between observed and forecasted precipitation (Pobs − Pmodel) made by the ECMWF model. It demonstrates a modeled overestimation of precipitation in large areas of Spain, especially in central and southeast areas, whereas on other areas the ECMWF precipitation was underestimated. In coastal and nearby areas, all the precipitation was in liquid form, where no significant undercatch due to wind was expected. In central Spain, where the precipitation was mostly in solid form, and following the southwest–northeast band of precipitation where the snowfall was more intense, the model shows an unexpected change of pattern; with increased elevation (and hence colder temperatures) the modeled precipitation changed from underestimated to overestimated.

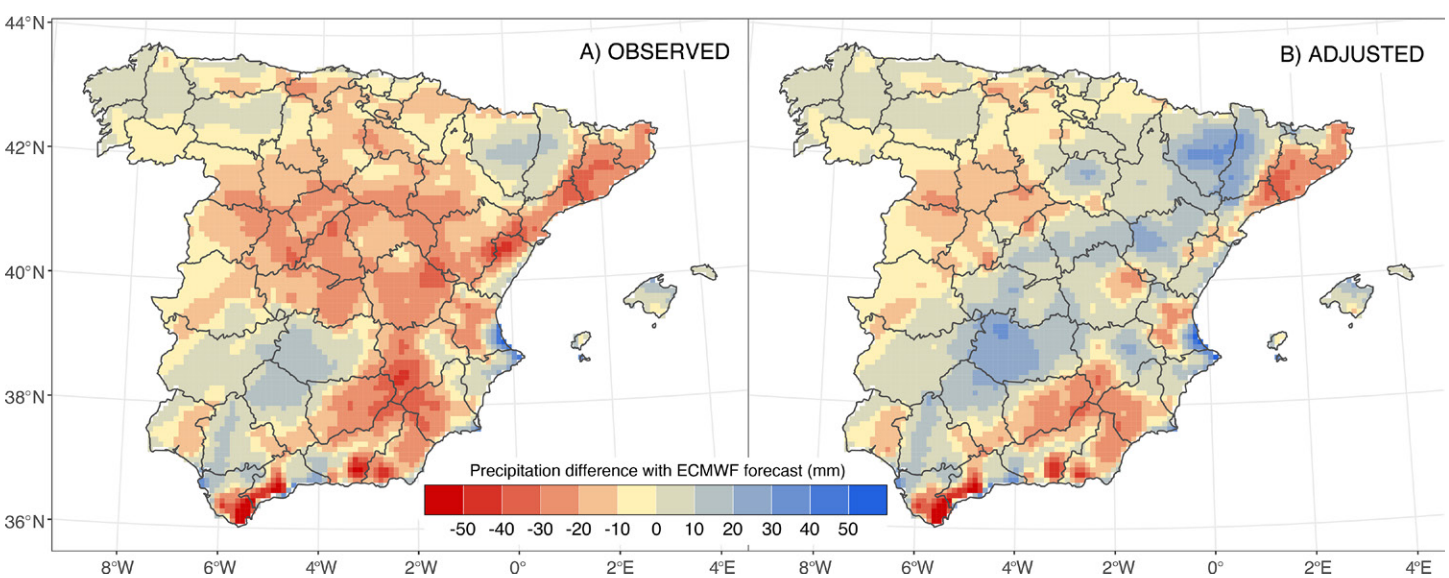


Fig. 8. Difference between observed/adjusted precipitation (mm) and precipitation forecasted by the ECMWF model during the Filomena event.

Figure 8b shows a more consistent pattern of underestimation/overestimation of the model when compared with adjusted observations, especially on the band of precipitation crossing central Spain from southwest to northeast. In addition, the abrupt change observed in Fig. 8a is gone. This figure allows a proper verification of the model product, helping to focus just on the numerical, meteorological, or topographic issues to appropriately assess the performance of the model during this period.

## Discussion and conclusions

The use of transfer functions to adjust solid precipitation measurements from operational gauges allows for the estimation of more accurate precipitation amounts. These adjusted measurements are more representative and consistent with the snow depth observed during snowfall events, especially during extreme events.

This work illustrates that proper quality control of the data and correct application of adjustments using available transfer functions provide a better understanding of extreme events such as Filomena. Such adjusted measurements are also beneficial for the verification of meteorological models.

These results show that an underestimation of 20–25 mm of solid precipitation in large areas of Spain was observed, with some areas experiencing even larger differences. Furthermore, without adjustments it was impossible to accurately validate the model forecast.

This works shows that using this methodology, the solid precipitation measurements were more consistent with the other available observations, and that the same method can be replicated for other snowfall events, occurring in other regions. An important element of this methodology is that good sensor maintenance and metadata within operational observation networks are needed to provide usable quality-controlled data.

This an example of the type of extreme events that modelers, forecasters, and climatologists should be aware of to avoid misinterpreting differences between forecasted precipitation, observed precipitation, and nowcasting. Satellite and radar precipitation validation studies must also consider these findings.

In addition, and perhaps most importantly, hydrologists must also consider the underestimation of solid precipitation measurements in their hydrology models, because this unmeasured precipitation is potentially hazardous. When an increase in air temperature and/or a liquid precipitation event occurs after a heavy snowfall, previously underestimated solid precipitation measurements can be particularly dangerous, as they can lead to unanticipated and destructive flooding. Fortunately, after Filomena, cold temperatures and a stable atmosphere resulted in a period of slow snowmelt that did not produce floods.

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