Precipitation analysis using disdrometer observations

Author: Eva Sintes Guardia
Advisor: Joan Bech Rustullet
Facultat de Física, Universitat de Barcelona, Diagonal 645, 08028 Barcelona, Spain.*

Abstract: This paper proposes an analysis of the Drop Size Distribution (DSD) measurements obtained during the 2013-2018 period with a laser-based optical disdrometer located at the weather stations of Barcelona and Das. Principally, the study focuses on the influence of the location and seasons on the DSD characteristics and consequently, in the variability of the relationship between the rainfall rate and reflectivity. Although the aim of this study is not to deduce a specific Z-R relationship, we illustrate its seasonal and spatial variability and decide if it is a good approach the use of a singular relationship throughout the entire observed period.

I. INTRODUCTION

The Drop Size Distribution (DSD) is a fundamental tool for the study of rainfall which allows us to improve our knowledge about the microphysical processes involved in rain-forming mechanisms and evolution or precipitation systems over time. Furthermore, it is of great practical importance for hydrological variables which can be derived from it such as accumulated precipitation, rainfall intensity or radar reflectivity.

There is a notable lack in the literature of DSD climatology studies performed in the Mediterranean region concerning the influence of several external factors like location, altitude, orographic influence, season or degree of convection in the microphysical and dynamical rain-forming processes that shape the DSD. Indeed, these factors lead to changes in the DSD and therefore in their calculated parameters and rainfall integral variables measured at the ground.

The most complete study of this type in the Mediterranean area was a recent study carried out in the southeast part of France, in the Cévennes-Vivarais Region [1]. The article summarizes a five-year DSD climatology of the region with the combination of three scaling parameters that fits the averaged DSDs: the characteristic diameter, the concentration and the shape parameter. The study demonstrates that the external factors analysed (location, season, daily synoptic weather pattern and rainfall type) influenced the DSD characteristics as well as the Z-R relationships.

The main objective of this paper is to perform a new long-term period study of the DSD climatology in the Mediterranean region of Catalonia with the data obtained from two Parsivel optical based disdrometers situated in different provinces. The first of them is placed in the meteorological station installed on the roof of the Physics Faculty of Barcelona at 98 meters above the sea level (MASL). The second disdrometer is located in the Pyrenees of Girona, in the meteorological station of Das, at 1097 MASL. There are significant differences between the two locations to take into account, like the different Mediterranean sub-climates. Barcelona presents a more coastal climate while Das is the clear example of mountain climate. In this way, it is important to take into account the influence of the altitude and the orography, leading to greater annual rainfall totals on the mountains.

By following the same line as the article of the DSD climatology for the region of the south-eastern France, we will carry out a similar study focused on the influence of two of the external factors mentioned above: seasons and location. The aim of this work is to find the main characteristics of these factors through the descriptor parameters of the gamma distribution chosen to represent the DSD and in the derived Z-R relationships.

II. DATA AND METHODOLOGY

A. Data collection

The data analysed in this study is provided by two generations of OTT Parsivel laser-based optical disdrometers [2][3] situated in the meteorological stations of Barcelona and Das.

The optical disdrometers measure the optical attenuation of a laser beam situated between a transmitter and a receiver when the raindrops pass through it. At the receiver, the laser signal is converted by a photodiode into an electric signal, and therefore, the attenuation caused by the particles will produce a decrease in the output voltage. Since the attenuation is proportional to the diameter of the particles which have blocked the beam, the amplitude of the voltage drop is related to the particle size. Moreover, the fall velocity of the particles can be estimated from the duration of the reduced output voltage.

The disdrometer registers the diameters and velocities for all the particles detected over the measuring period of time and store it as an array whose dimension is the number of diameter classes by the number of velocity classes. The instrument cannot differentiate between velocities and diameters within the same interval, so the mean value of the interval is assigned to all particles recorded in it. In our case, the type of disdrometer used could distinguish between 32 diameter classes (with mean values ranging from 0.062 to 24.5 mm) and 32 velocity classes (with mean values from 0.05 to 20.8 m/s), with a resultant array of 32x32 elements. In this study, the raw output arrays represent the total number of particles recorded for each diameter and velocity class in a sample time of 1 min.

Via this functioning, the disdrometer allows us to obtain information about the rainfall from their calculated drop size distributions. In this way, it is possible to determine the parameters of interest for this study such as the equivalent radar reflectivity and the rain rate from the measured DSDs.

B. Correction methods and filtering

Parsivel disdrometers can present some errors in the recorded number of drops which causes overestimations of large drops and underestimations of small drops in more intense rain rates [4][5], leading to misstatements in the derived rainfall variables.

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* Electronic address:`esintegu7@alumnes.ub.edu`

In order to improve the experimental measurements, the correction method developed by Raupach and Berne [6] has been applied to the Parsivel raw data. This correcting method consists of comparing the results obtained by Parsivel disdrometers with a two-dimensional video disdrometer (2DVD) using this latter as a reference. The first step of the method consists in correcting the mean drop fall velocities for each diameter class so that it matches with the theoretical models of terminal velocities for raindrops of that diameter. After that, the data is processed in order to filter the recorded particles for which diameters and terminal velocities are unlikely to be raindrops. These wrong measurements could be caused by external sources of error. The second step is to apply to the calculated volumetric drop concentrations per diameter class a pre-determined set of adjustment factor which, being multiplied by the raw array data of Parsivel, leads to similar values obtained with the 2DVD, used as a reference. The results in [6] showed an improvement in the accuracy of the measured DSDs using this correction method.

After this correction, two additional filters have been applied to the resultant data. The first has been to filter out the solid and mixed (liquid and solid) particles. The information required about the type of hydrometeor (rain, snow, sleet, etc. up to 8 types and with different intensities for each type) is given by the Parsivel itself. For the purpose of this study, only the time steps for which the rainfall rate was higher than 1 mm/h are selected.

C. DSD descriptor parameters

The drop size distribution or N(D) is defined as the number of raindrops per volume and diameter interval ($mm^{-1}m^{-3}$). Several integral parameters are calculated from the moments of order k of the DSD. These moments are defined by the expression:

$$M_k = \int_0^\infty N(D) D^k dD. \tag{1}$$

One of the most widely used model to represent the DSD is the three-parameter gamma model:

$$N(D) = N_0 D^\mu \exp(-\lambda D) \tag{2}$$

where N_0 ($m^{-3}mm^{-1-\mu}$), μ (dimensionless) and λ (mm^{-1}) are the concentration, distribution shape and size parameters, respectively. In many cases, this model allows a better fit of the distribution for a wide range of shapes or rainfall situations, with respect to the Marshall-Palmer two-parameter exponential distribution (obtained by setting μ=0 from the gamma distribution).

A normalized formulation called the "normalized DSD" is introduced by Testud [7] in order to avoid the dependence of N_0 with μ:

$$N(D) = {N_0}^* D^\mu \frac{\Gamma(4)(4+\mu)^{4+\mu}}{4^4\,\Gamma(4+\mu)} \left(\frac{D}{D_m}\right)^\mu \exp\left[\left(-\frac{(4+\mu)}{D_m} D\right)\right] \tag{3}$$

where N_0^* represents the new scaling parameter for the DSD concentration expressed in $m^{-3}mm^{-1}$, now being independent of μ, and D_m is the mean volume diameter in mm. D_m is related to the slope parameter λ by $D_m = (\mu + 4)/\lambda$.

Three moments are needed to determine the three scaling parameters for the gamma distribution: M_2, M_3 and M_4. From these moments, the set of parameters that define the gamma function are calculated:

$$D_m = \frac{M_4}{M_3} \tag{4}$$

$${N_0}^* = \frac{4^4}{\Gamma(4)} \frac{{M_3}^5}{{M_4}^4} = N_0 {D_m}^\mu \frac{\Gamma(4+\mu)}{\Gamma(4)} \frac{4^4}{(4+\mu)^{4+\mu}} \tag{5}$$

$$\mu = \frac{3M_4M_3 - 4{M_3}^2}{{M_3}^2 - M_4M_2}. \tag{6}$$

The spatial and temporal variability of the three scaling parameters chosen in this study to characterize the DSD (N_0^*, D_m and μ) have been analysed using box-and-whisker plots in order to compare more easily the behaviour of data.

D. Z-R relationship

The rain rate R (mm/h) and the radar reflectivity factor Z (mm^6m^{-3}) are related theoretically to the statistical moments of the observed DSD's by the following equations:

$$Z = \int_0^\infty N(D) D^6 dD \tag{7}$$

$$R = \frac{6\pi}{10^4} \int_0^\infty N(D) v(D) D^3 dD \tag{8}$$

where v(D) is the terminal fall velocity of a raindrop of diameter D, expressed in meters per second.
The Z-R relationship relate these two magnitudes, the measured reflectivity to the value of rain rate, by the generalized form of Marshall and Palmer relation [8]:

$$Z = A R^b \tag{9}$$

where the prefactor A and the exponent b are empirical parameters. It is shown from previous studies [9] that there is not a unique Z-R relationship due to their highly dependence on the rainfall characteristics, and therefore on DSD parameters and their variability. Thus, the large dispersion observed in the coefficient A and exponent b values for the Z-R relationships is due to a wide range of factors which to a greater or lesser degree could affect/modify the experimental DSDs: climatic area, location, orographic environment, rain type (convective or stratiform), synoptic situation or seasons, among others.

In the study, the Z-R relationships have been calculated by linear relationships between the logarithms of Z and R through least squares method:

$$dBZ = 10\log(A) + b\,dBR \tag{10}$$

where $dBZ = 10\times\log_{10}(Z)$ and $dBR = 10\times\log_{10}(R)$ are expressed in decibels of Z and R respectively, and 10log(A) and b are the intercept parameter and the slope, respectively, for the linear regression in the log-log plot. In order to observe the variability of Z-R relationship, dBZ and dBR are represented as a scatterplot computed from 1-min DSD data with the 80% confidence ellipses.

III. RESULTS AND DISCUSSION

The variability associated with the influence of the external factors of seasons and location is studied for the Z-R relationship and the three scaling parameters defined in (4), (5) and (6) that characterize the DSD. For that purpose, we have grouped the months by meteorological seasons: December, January and February are grouped and labelled as winter; March, April and May as spring; June, July and August as summer; and finally September, October and November as autumn. This seasonal analysis is carried out for data collected in two different locations, Barcelona and Das.

A. Barcelona

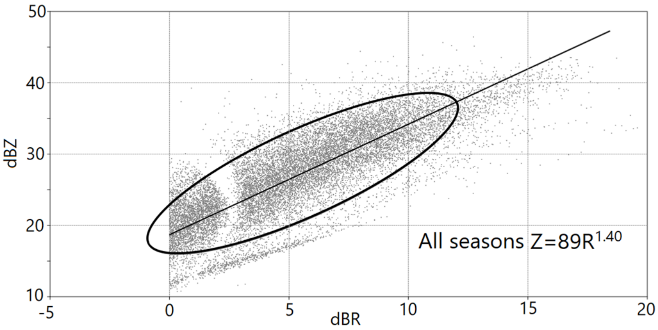


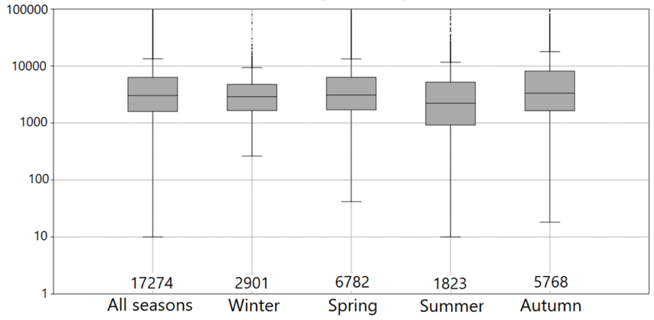
FIG. 1: Z-R scatterplot computed from the 1-min rainy time steps recorded during the entire analysed period in Barcelona (2013-2016). The 80% confidence ellipse of the scatterplot is also displayed.

Fig.1 shows the 80% confidence ellipse of the dBZ-dBR scatterplot for all the recorded data during the observed period in Barcelona (2013-2016). The Z-R relationship has also been calculated by isolating A and b from the linear regression in (11). The distributions of the three scaling parameters (N_0^*, D_m and μ) for the entire period of time are represented, respectively, in (a), (b) and (c) of Fig.2 and labelled as “all seasons”.

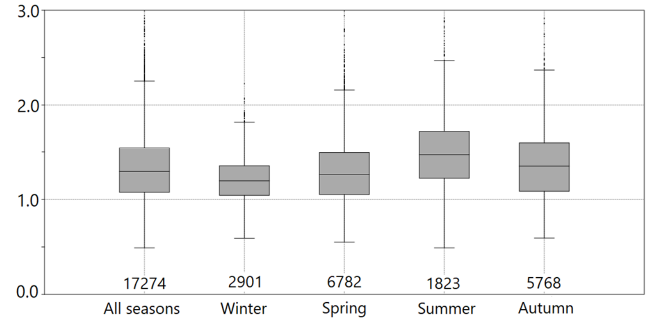
Fig.2 and Fig.3 display the variability that appears on the DSD parameters and Z-R relationships if the recorded data is analysed separately by seasons. The most appreciable features that appear are as follows:

- Summer season is clearly different from others, with higher mean diameters and lower drop concentrations, being the season which presents the largest dispersion for these parameters. These marked differences are also appreciated for summer Z-R relationship in Fig.3, which presents a high prefactor A and low exponent b compared to the other seasons. The higher diameters leads to a visible shift in the pertinent ellipse toward higher values of Z for low to moderate rain-rates.
- Winter stands out for presenting the lowest dispersions for the three scaling parameters and the lowest values for D_m. While the quartiles Q1 and Q2 for N_0^* are very close to those of spring and autumn, Q3 is slightly lower. From fig.3 we could see that there are less extreme values for the rain-rates in this season.
- Spring and autumn have intermediate values between winter and summer for D_m and fairly high values for the quartile Q3 of N_0^*. The 80% confidence ellipse of the Z-R plot during spring has similar orientation to that of winter, but with higher rain-rates values. Despite the fact that values for the mean diameter and concentration parameters are fairly high during autumn, the Z-R relationship shows a low prefactor and strong exponent, leading to a shift for the 80% confidence ellipse toward smaller values of Z in the range of low to moderate rain-rates.
- From Fig. 2 (c) we can see that the seasons have a small influence on the shape parameter, only the quartile Q3 is slightly higher during autumn and slightly lower during winter.

(a) N_0^* [$m^{-3}mm^{-1}$]



(b) D_m[mm]



(c) μ [-]

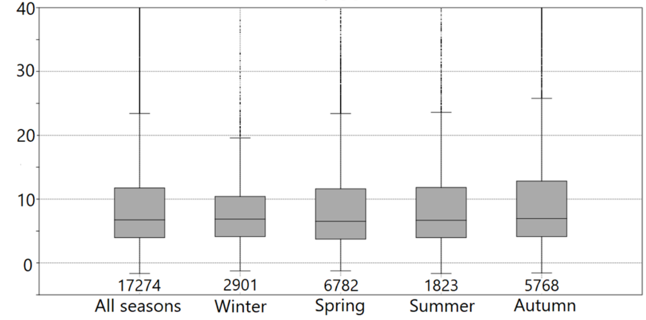


FIG. 2: Influence of seasons on: **(a)** concentration, **(b)** mean volume diameter, and **(c)** shape DSD scaling parameters in Barcelona. The box plots represent the median (Q2) and the lower and upper quartiles (Q1,Q3). The lower limit indicates the minimum value and the upper limit indicates Q3 + 1,5(Q3-Q1). Values greater than the upper limit are the outliers. The number of one-minute rainy time steps analysed for each case has been added in the lower part of box-plots.

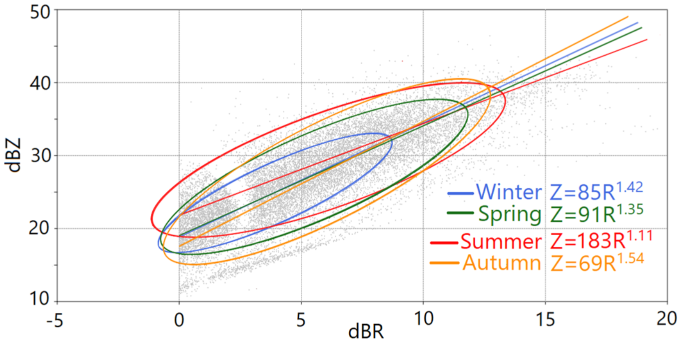


FIG. 3: Influence of seasons on Z-R relationship.

Comparing the general Z-R relationship obtained from all recorded data (shown in Fig.1) with the specific Z-R relationships obtained by each season separately (shown in Fig.3), we can appreciate some peculiarities: winter and spring have almost the same values for the prefactor and exponent as the general Z-R relationship, while summer and autumn presents more differing values. Summer presents the most differentiated relation with higher prefactor and lower exponent, whereas autumn has the smallest prefactor and the highest exponent. One possible first explanation for these Z-R parameters variability might be the relatively high number of convective or stratiform rain events associated with these seasons. To study this possibility, the C/S discrimination algorithm proposed by Caracciolo [10] for mid-latitudes has been applied to our data. This C/S discrimination takes into account four sort types for rainfall, and is based on the following criteria:

- If $R < 10$ mm h^{-1} and $Z < 38$ dBZ: S rain
- If $R > 10$ mm h^{-1} and $Z < 38$ dBZ: heavy S
- If $R \geq 10$ mm h^{-1} and $Z \geq 38$ dBZ: C rain
- If $R < 10$ mm h^{-1} and $Z > 38$ dBZ: shallow C

Season	Rainy time steps (min)	S rain (%)	Heavy S (%)	Shallow C (%)	C rain (%)
Winter	2091	98,800	1,148	0,000	0,048
Spring	6782	87,585	9,422	0,811	2,182
Summer	1823	81,514	13,330	1,755	5,595
Autumn	5678	84,379	10,558	0,503	4,560

TABLE I: Percentages of rainfall regime occurrence for each season. The C/S discrimination algorithm differences four rain regimes: stratiform(S), heavy stratiform (heavy S), shallow convective (shallow C) and convective (C) rain.

From Table I we can appreciate how summer has the higher percentage of convective type events. This fact can explain the peculiarities found for A and b parameters in this season, in concordance to those found by studies performed in similar latitudes, such as the south-east France [1] and Italy [10], where stronger prefactors and a quite low exponents are characteristic of convective mid-latitude precipitations. In contrast, the season of winter presents stratiform rains for more than 99% of time. These type of rains are characterized by low A values associated with high b values. In this sense, a clear disagreement is found by the results obtained for autumn, because it presents the lowest prefactor and the highest exponent of the seasonal Z-R relationships, even being the second season with more convective rainy time steps. These A and b values cause the discrepancy that we have seen for their 80% confidence ellipse, which is shifted toward lower values of Z for low to moderate rain-rates despite their relatively large mean diameters. The main cause of this disagreement comes from the least squares fitting technique used to calculate the Z-R relation-ships, which is clearly not well suited for autumn season, due mainly to data obtained from November of 2013. If we remove data from the 15th and 16th of November, then the linear regression is well adjusted, leading to a differentiated Z-R relation, $Z=114R^{1.33}$, with greater concordance with the results.

To get an idea of the microphysical dominant processes that could take place, we have used as a reference the studies of Rosenfeld and Ulbrich [9] and Dolan [11], who related the different microphysical rain-forming processes (such as coalescence, evaporation, breakup, updraft…) with their effects on Z-R relationships and DSD scaling parameters. Thus, peculiarities found in summer (high mean diameters, low concentrations and larger reflectivities) could be associated with convective precipitation processes such as rain warm processes dominated by collision and coalescence or ice-based processes supported by strong updrafts, while that of winter (light rain rates and small mean diameters) could be caused by vapor deposition rain-forming processes.

B. Das

The same seasonal analysis is carried out for winter and spring in the meteorological station of Das during 2016-2018.

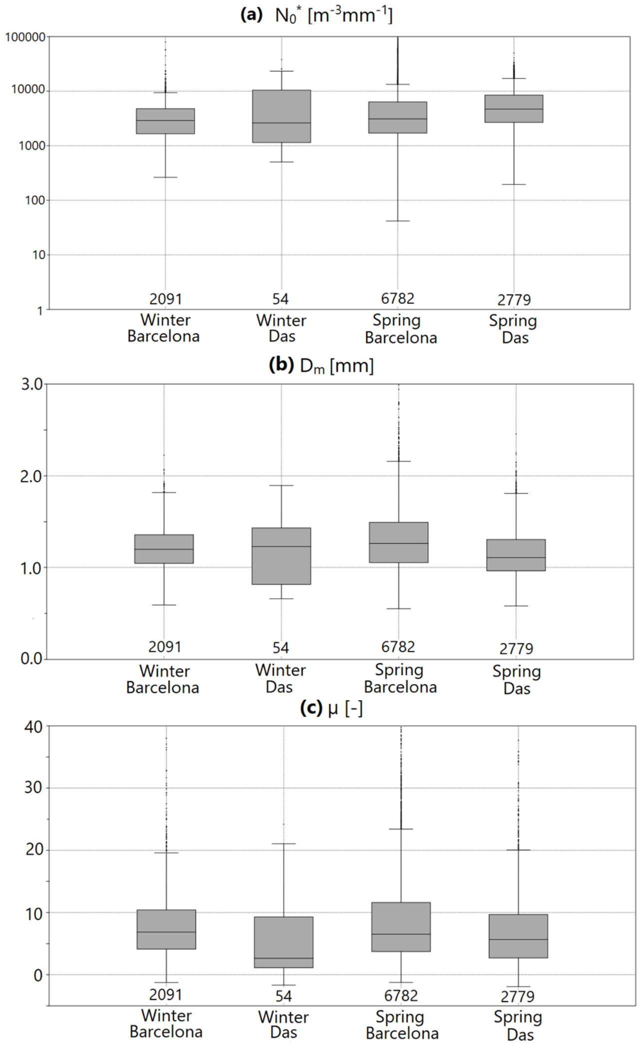


FIG. 4: Influence of seasons (winter and spring) on: **(a)** concentration, **(b)** mean volume diameter, and **(c)** shape DSD scaling parameters in Barcelona and Das.

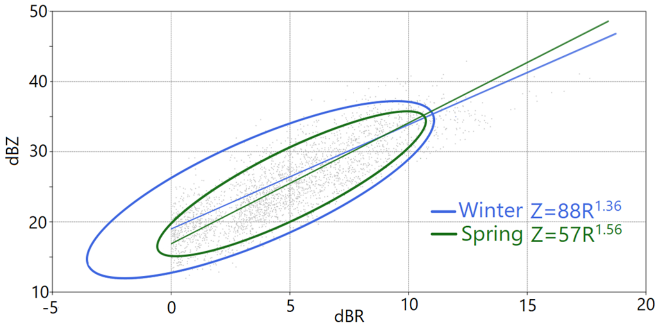


FIG. 5: Influence of seasons (winter and spring) on Z-R relationship

Fig.4 and Fig.5 show the distributions of DSD parameters and Z-R relationships if recorded data is analysed separately by seasons. For this location, only the influence of seasons of winter and spring has been analysed because we only have available data from those months. Moreover, there are very few rainy time steps after solid particles filtering for winter due to the low temperatures during this season in Das. As a consequence of that, the interquartile [Q1,Q3] of N_0^*, D_m and μ distributions and the 80% confidence ellipse exhibit large dispersions, so we will focus especially on spring season for the analysis. In order to facilitate the comparison between Barcelona and Das, the box-plots of both locations are represented. The principal differences which can be seen are:

- A notable tendency in the variability of the scaling parameters between two locations: Das presents higher values of N_0^* and lower values of D_m and μ compared to Barcelona.
- Winter Z-R relationship for Das in Fig.5 is similar to that of Barcelona, while spring presents a substantially different relation, with lower prefactor and stronger exponent. There are also lower rain-rates values for spring in Das.

These differences between two locations are principally associated with their different geographical environments. The terrain of the region could have an impact on the rainfall characteristics, and therefore, on their observed DSD, leading to a variability in the parameters and relations obtained from it. Since Das is located in a mountainous area, the larger concentrations and smaller mean diameters found here are likely associated with a specific type of rain: orographic rain. Orographic precipitations tend to be characterised by smaller prefactors and larger exponents for their Z-R relationships [12], in agreement with the relation obtained here for spring.

IV. CONCLUSIONS

The DSD climatology analysis carried out in Barcelona and Das from the DSD properties according to the influence of external factors studied shows that:

- Seasons have a significant influence over the concentration and diameter scaling parameters as well as on Z-R relationships, especially for summer, which presents a differentiated Z-R relation as a consequence of a greater number of convective episodes during this season, characterized by larger drops and lesser concentrations.
- Barcelona presents a similar behaviour in the variability of N_0^* and D_m scaling parameters and Z-R relationships under seasonal influence as that found for the Cévennes-Vivarais Region [1]. That is, with more variability for summer season and intermediate characteristics for D_m and Z-R relations between winter and summer for autumn and spring. These seasonal similitudes could be associated with the fact that both regions are under the influence of the Mediterranean climate.
- Locations with different altitudes and orographic environments show differences in their associated DSD. It is found that the concentration parameters are higher and the mean diameter and shape parameters are lower in the mountainous region of Das. The particular Z-R relationship found for spring in this region, with low prefactor A and strong exponent b, together with smaller mean diameters and larger concentrations could be associated with the presence of orographic rains.
- From the results obtained in the study it is observed how reflectivity-rain rate relations (Z-R) vary from season to season and one location to the other. From these facts, we can conclude that could be an advantage to derive specific relationships for seasonal periods and at given locations in order to improve rainfall radar measurements using the Z-R relationship.

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