

Article

Variations in Seasonal Precipitation Patterns with Elevation in Catalonia (2016–2025)

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Abstract

Catalonia has a Mediterranean climate with intense, long drought or rainy periods, which are difficult to manage. The variable topography and sea conditions also help modulate the extreme atmospheric regime. The aim of this research is to model the regional precipitation regime using different radar and lightning fields. To conduct the analysis, several points at different heights have been selected to evaluate monthly values and establish common yearly patterns. It has been observed that there are two principal behaviours from the maxima: single and double modes. The single peak usually occurs during warm months (mainly July and August), meanwhile the bimodal maxima are concentrated in spring (March) and autumn (October or November).

Keywords: precipitation; weather radar; lightning; Catalonia; topography

1. Introduction

According to the World Meteorological Organisation (WMO), extreme weather in Europe and the Mediterranean Basin in 2025 was marked by significant droughts, extreme wildfires, floods, and severe windstorms [1]. The report also indicates an increasing number of extreme weather cases in the region, associated with the rising average temperature observed over the last few decades. These adverse conditions require taking immediate action. For instance, it is necessary to collect as much information as possible about the current meteorology. Therefore, this allows the comparison of those values with historical data, facilitating the management of hydro-meteorological resources in one of the most densely populated areas [2–4].

Mediterranean Basin countries have historically experienced floods, caused by the meteorological and geographical conditions [5–8]. Among the meteorological causes, we can find extreme weather conditions. In this way, long dry periods produce warm air masses. The combination of these with some moist advections changes the nature of the lower-level atmosphere. Then, the instability produced by cold air at high levels or, for instance, an extra-tropical cyclone irruption is the triggering element that develops highly efficient thunderstorms [9–11]. The large cumulated values combined with arid soil conditions and small, fast response of basins cause dramatic floods that affect infrastructure, such as highways and buildings, but can also impact the population [12–14].

Several authors have shown that topography is one of the conditions that modulate rainfall regimes [15–18]. Precipitation usually increases with altitude, but only until a certain level, which is considered the breaking point in the rainfall trend. The height of the breaking point is not equal in all regions. In addition, it depends on the climatic conditions [19–21]. Among these, oceanic waters also participate in the water cycle, partic-



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ularly warm ones such as the Caribbean Sea, the Chinese Sea, the Australian Sea, or the Mediterranean Sea [22–26].

Catalonia has a high rainfall variability along different parts of the territory, not only in total accumulated yearly precipitation but also in other variables such as the consecutive dry (non-rainfall) days [27]. Drier regions usually correspond with the mid-southern part of the territory, while the more humid areas are in both extremes (west and east) of the northern sector. In the same direction, Bustins et al. [28] showed that torrential episodes occurred mainly in moist areas, but also in dry ones, where yearly precipitation can be concentrated in a few days (coinciding with Martínez et al. [29]). Reference [29] also focused on the high variability of precipitation for the different parts of Catalonia, with high values of the standard deviation in the mountainous areas. However, the more intense events occurred in the southern coastal area, but they were also possible in the rest of the litoral and northeastern mountain ranges. All the previous studies assumed that the interaction between topography and the sea was the main modulator of this variability. In addition, climatic factors can also play a relevant role in the precipitating field, but with less impact on the results. Regarding lightning activity, Pineda et al. [30] observed that the starting area usually corresponds with the highest peaks of the northeastern ranges. Later, thunderstorms move to flat areas, where the activity increases, reaching the highest flash density values. However, the southern and central coastal and prelitoral areas can reach high flash density values, especially during the later part of summer.

The aim of this research is to show changes in the yearly precipitation regime in Catalonia. To do this, different radar and lightning parameters have been selected for the period 2016 to 2025 (both years included). These parameters have been evaluated at different points considering the altitude to categorise them. The variables have been evaluated daily for each category, using the mean value for the different points.

2. Materials and Methods

2.1. Area of Study

Catalonia is in the northeastern Iberian Peninsula, covering 32,000 km² (Figure 1a). The region's topography is abrupt, ranging from 0 m at the coast to over 3000 m ASL (Above Sea Level) in the north (Figure 2a). Several valleys and plains are surrounded by different ranges. These features are like those of other Mediterranean areas [31–34]. From a hydro-meteorological viewpoint, heavy rainfall events are frequent in Catalonia, producing flash floods or floods, depending on the nature of the rainfall event [35,36]. Catastrophic episodes have historically caused significant damage and casualties, with major impacts on hydrologic structures [37,38]. Furthermore, prolonged drought episodes have repeatedly led to societal problems [39,40].

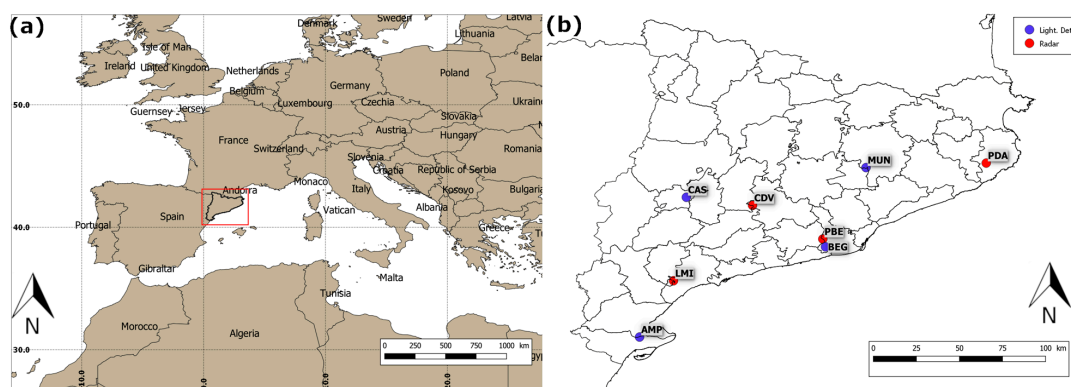


Figure 1. (a) European map with Catalonia inside a red rectangle. (b) Zoom to Catalonia with blue dots indicating Lightning Location Systems and red points showing the radar positions.

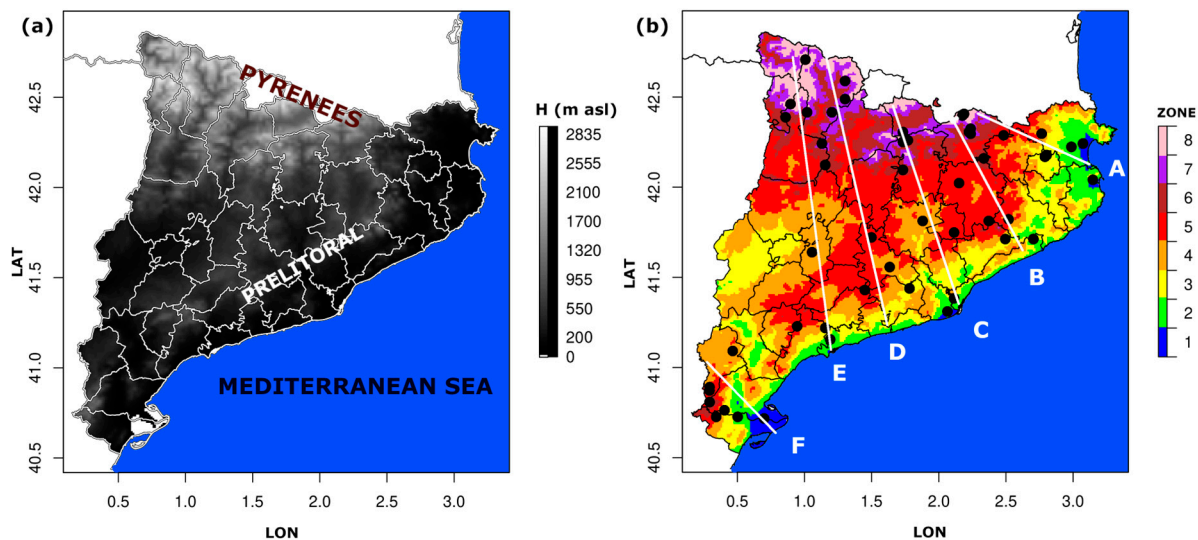


Figure 2. (a) Topography of the area of study. (b) Different selected zones with the black dots indicating the locations of the positions selected for the analysis. The white lines indicate the transects (labelled from A to F, from north to south) considered for selecting the points from sea to inland.

2.2. Data

As many previous works have shown [41,42], the region of study is well covered by two remote sensing networks, used in the present work (Figure 1b). Both networks belong to the Meteorological Service of Catalonia (SMC, Servei Meteorològic de Catalunya in Catalan), and both of which has operated since the early 2000s [43]. First, the weather radar network (XRAD) is composed of four C-band single-pol systems that produce volumetric scans every 6 min, with 15 elevation angles from 0.6 to 30°, with a range of 130 km from the radar. The composite of all four radars provides a complete vision of the atmospheric conditions from the surface to nearly 20 km ASL, with a horizontal grid of 1 km × 1 km.

The second network is a passive remote sensing system: it only provides information in the case of lightning activity [44]. The Lightning Location System (XDDE, Xarxa de Detecció de Descàrregues Elèctriques) operates in two frequency ranges (low frequency, LF, and very high frequency, VHF) to provide the locations of cloud-to-ground (CG) and intra-cloud (IC) flashes produced by thunderstorms. The detection efficiency (DE) is close to 95% for CGs and 80% for ICs over the Catalan terrain, decreasing detection quality as the thunderstorm moves farther from the network. The location precision is close to 500 m for CG flashes; meanwhile, for ICs, it ranges between 1000 and 2000 m across the Catalan territory. Figure 1b shows the location of the four detectors.

The research has consisted of the analysis of different radar products [45–48], from reflectivity at the surface (ZSF) and the maximum value for the complete column (ZTO), the echo top (or the maximum height where an echo exceeds a certain reflectivity threshold) for 12 dBZ, 35 dBZ, and 45 dBZ (T12, T35, and T45), the quantitative precipitation estimation at daily and 30 min time resolutions (RNN and R30), and the VIL (Vertically Integrated Liquid) density (VILD). Reflectivity provides an estimate of the instantaneous rainfall intensity, echo tops provide information about the vertical development of precipitation structures, rainfall estimation produces an accurate map of the precipitation distribution, and VIL density indicates whether hail is possible in a thunderstorm. Except for rainfall products, the time resolution is 6 min (10 fields hourly). The period of analysis is 2016 to 2025 (10 years in total). The earliest available date for all the sources is 2013. Year 2006 is the initial date for lightning data, and there are radar fields prior to 2013. However, the SMC started an operational database with all the products in geotiff format for that year. The initial date selected was 1 January 2016 to consider a complete 10-year period.

In the case of lightning data, only CG flashes have been considered to reduce the location problems associated with IC lightning. Therefore, thunderstorm activity has been taken into account for those flashes touching ground level, in a similar way to Taszarek et al. (2019) [49].

2.3. Methodology

To evaluate the different radar and lightning fields depending on the topography, a series of points (Figure 2b) has been selected, placed at heights of eight different ranges:

- * Zone 1: Between 0 and 5 m ASL (coastal plain);
- * Zone 2: Between 5 and 100 m ASL (coastal line or valleys);
- * Zone 3: Between 100 and 250 m ASL (low prelitoral ranges or internal planes);
- * Zone 4: Between 250 and 500 m ASL (high prelitoral ranges or elevated planes);
- * Zone 5: Between 500 and 1000 m ASL (very high prelitoral ranges);
- * Zone 6: Between 1000 and 1500 m ASL (mid internal ranges);
- * Zone 7: Between 1500 and 2000 m ASL (mid Pyrenees and high internal ranges);
- * Zone 8: Over 2000 m ASL (high Pyrenees).

The different ranges have been selected according to the topographic conditions of the region, which are defined in the internal handbook of the Meteorological Service of Catalonia. The different zones have specific meteorological conditions that must be considered at the time of generating issues of adverse weather conditions.

We considered different segments (see Figure 1b), ranging from the Mediterranean Sea to the Pyrenees (A to E), and included an additional segment in the southern area (F). This selection ensures enough points from the various zones to validate the research goal. In addition, the different transects were based on the previous studies of the region [27–30]. A daily value was obtained for each point of the different radar and lightning products for the period 2016 to 2025. The punctual values were extracted using the raster library [50] from the software R (version 4.4.3) [51]. For the radar variables, the value was the daily maximum, except for rainfall, for which the total accumulated value was selected. In the case of the lightning field, the number of flashes registered over the pixel was obtained.

Therefore, each field produces 1336 values for 51 selected points (3 from zone 1, 5 from zone 8, 6 from zones 2 and 3, 7 from zones 4 and 7, 8 from zone 5, and 9 from zone 6). The number of values corresponds to the days with rainfall exceeding 1 mm in the area. It is 36.6% of the days in total. Zones 1 and 8 have fewer points because of their smaller size. However, it was important to consider them a part of the rest because of their nature. Also, it is relevant to say that even though there are some close points (with distances below 5 km), they have been selected because the classification zone was different or, if it was the same, the difference in height was larger than 50 m.

For each date of the 1336 selected cases, all data are available (i.e., with a non-null value) for each zone. Therefore, all the values of each zone have been considered in the first section of the study. The outliers have also been obtained from the general dataset to select those anomalies in the general behaviour. This is important because the mean or maximum daily values have been considered; the percentiles have been masked. Finally, the same analysis has been conducted for months to determine the yearly regime of each variable. Again, all the values have been considered, and there are differences between the monthly datasets, but these differences agree with the possibility of heavy rainfall events occurring. For instance, January has only 48 valid values for the total reflectivity, while June has 166. Consequently, the results are more robust for the months from April to October, but for the rest of the year, events are less frequent and less adverse.

The general behaviour of each variable has been evaluated globally for the different regions to identify some discriminating characteristics associated with the changing altitude.

Then, the monthly evolution of some parameters has helped to reach important conclusions regarding the changes for the different variables and zones. This variability has been related to the precipitation regimes and topography.

3. Results

3.1. General Results

The different panels of Figure 3 are associated with the precipitation regime: surface reflectivity (a) can be associated with the ground precipitation intensity, total reflectivity (b) is the maximum intensity in the full radar column, daily quantitative precipitation estimation (c) estimates the total precipitation during a day, and 30 min quantitative precipitation estimation (d) measures the semi-hourly intensity. The violin plot [52] visualises the combination of a box plot with a kernel density estimate. Therefore, it is like a box plot, but the different widths at various heights of the sample marks indicate the more typical values. It can be observed that for the reflectivity fields (top panels), the values increase with height from zones 1 to 4. This is the breakpoint, and from here, reflectivity values gradually decrease. Therefore, a breakpoint is defined in this research as the level at which the variable trend clearly changes. This is a variable that goes from a positive to a negative trend (or vice versa). Similarly, quantitative precipitation estimation also increases. However, the breakpoint is zone 6 for the daily field and zone 5 for the 30 min product.

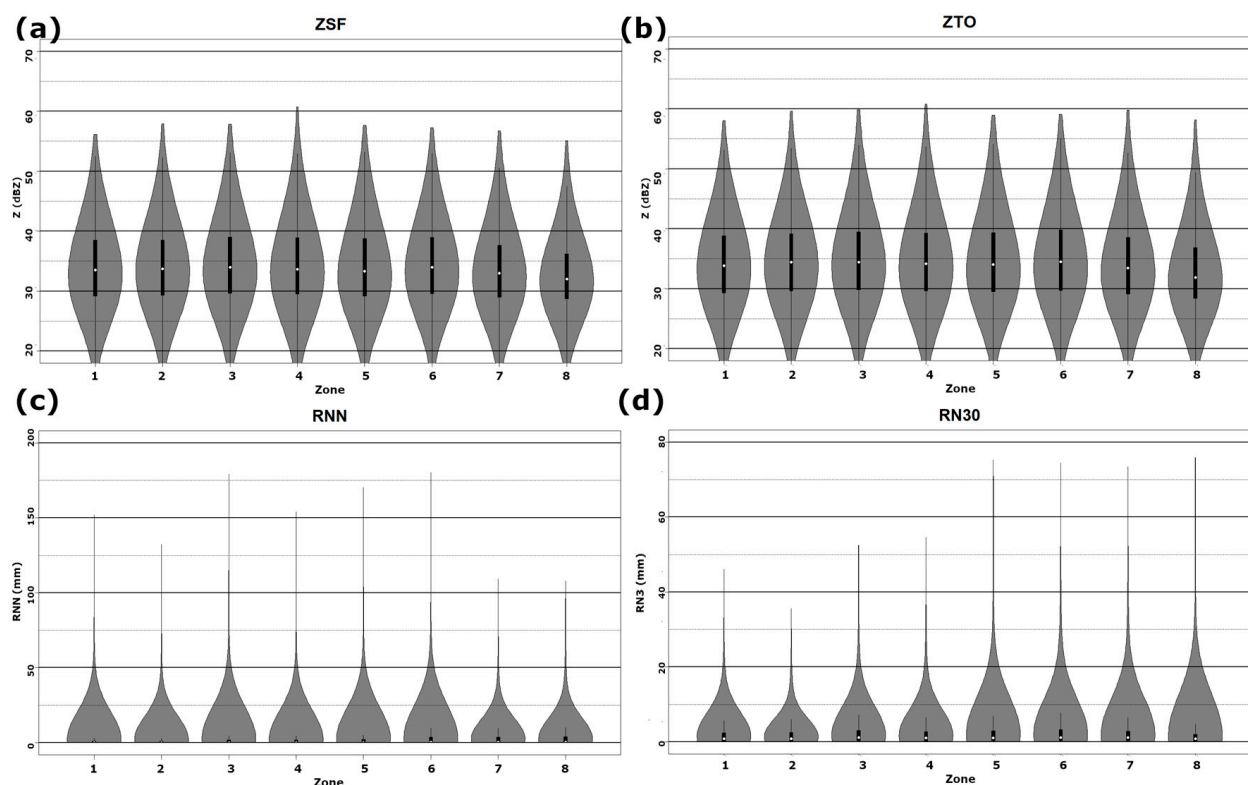


Figure 3. Violin plots for the different zones presented in Figure 2, for surface reflectivity—ZSF (a), total reflectivity—ZTO (b), daily quantitative precipitation estimation—RNN (c), and 30 min quantitative precipitation estimation—RN30 (d). Black boxes indicate the box plots, and the white dots correspond to the median value.

Figure 4 shows variables associated with the development of the precipitating systems (echo top for three different reflectivity thresholds: 12 dBZ for all precipitation, 35 dBZ for mid-intense rainfall, and 45 dBZ for high-rain rate precipitation, according to the experience of the Catalan Meteorological Service staff) and with the probability of hail in

thunderstorms (VIL density). In all cases, higher TOP values occur in zone 3. However, the maximum median value for the violin plot is located between zones 7 and 8. This means that the higher development of thunderstorms occurs when the systems are in low regions, but the systems observed in higher regions tend to be more developed in general. Finally, the diagnosis of hail shows the largest values of DVIL between zones 3 and 4, while the largest median values are recorded in zones 5 and 6. Then, mid-topography has a main role in hail occurrence, particularly at the highest peaks.

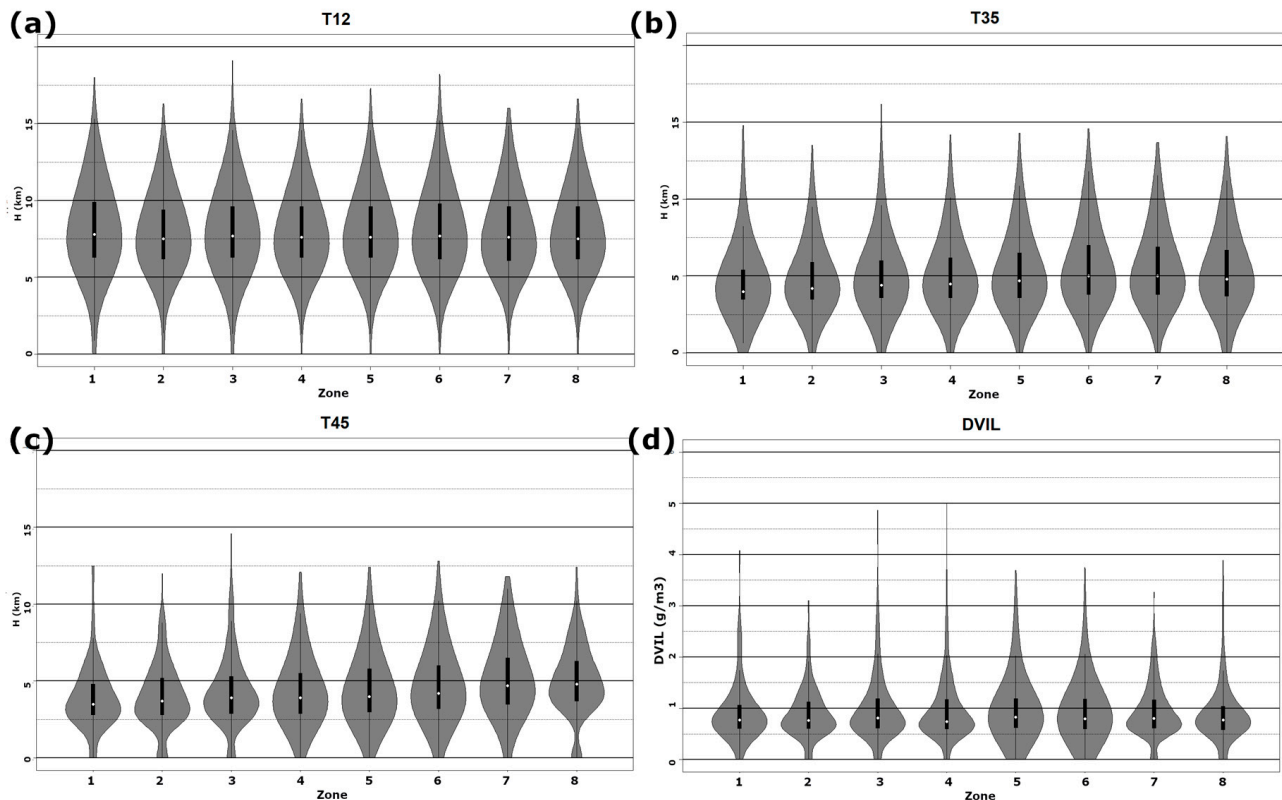


Figure 4. Same as Figure 3, but for echo top 12—T12 (a), 35—T35 (b), and 45—T45 (c), and VIL density—DVIL (d).

Figure 5 provides a summary of the electrical activity for the different zones. In this case, two principal regions are distinguished: the first is the flattest one, zone 1, indicating the high contribution of the Mediterranean Sea in the electrification of precipitation systems. The second one corresponds to the top zones (6 to 8), where the electrical activity is notably more important than in the mid-topographic regions.

To go more in depth with the previous results, Table 1 shows the upper level of the internal black box around the median (white dot), corresponding to the 90th quantile. This parameter has been estimated for the eight zones for the nine products. In general, higher values are concentrated in the upper regions (zones 6 to 8) for most variables (TOP12, TOP35, TOP45, RNN, RN30, and ZTO). On the other hand, XDD (electrification) is more important in flat areas, while VIL density and surface reflectivity have the predominant range between zones 3 and 6. The bold values in the table indicate the breakpoints for each variable, observing how for echo tops moves between 1000 and 2000 m ASL (the principal vertical developments occur near the peaks of the higher ranges); for lightning the breakpoint occurs in the coastal area, which plays a main trigger for convection; large rainfall values are usually observed in the higher zones (over 1000 m ASL); the higher probability of hail (DVIL) is observed in the inland planes and mid-ranges (between 100 and 1500 m ASL); and the higher intense precipitation (reflectivity) has a similar behaviour

than DVIL. In consequence, the topography and coastal lines play a major role in the modulation of the rainfall regime of the region.

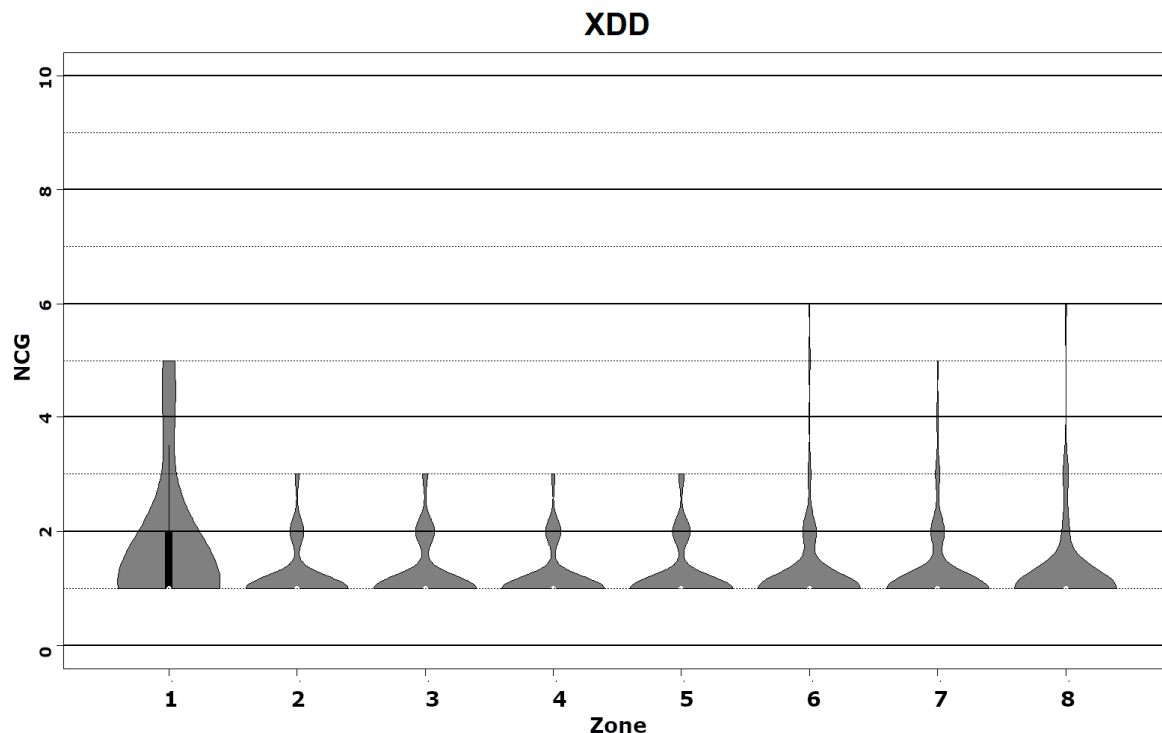


Figure 5. Same as Figure 3, for CG lightning.

Table 1. Values of the 90th quantile for the different variables and zones. Bold values indicate the breakpoints for each variable.

Variable	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Zone 6	Zone 7	Zone 8
TOP45	7.8	8.8	8.9	9.4	10.0	10.2	11.0	10.2
TOP35	8.3	9.5	9.6	10.1	10.9	11.8	11.6	11.2
TOP12	15.3	14.2	14.6	14.6	14.6	15.2	14.9	14.7
XDD	3.5	1.0	1.0	1.0	1.0	1.0	1.0	1.0
RNN	2.9	3.0	4.4	4.4	5.0	9.3	9.4	9.9
RN30	2.3	2.5	3.7	3.2	3.3	4.8	4.2	3.3
DVIL	1.7	1.9	2.1	2.0	2.0	2.1	2.0	1.7
ZSF	52.5	52.3	53.1	53.0	53.2	53.0	50.6	47.5
ZTO	53.1	53.4	53.9	53.7	54.1	55.0	52.7	49.5

Applying a Welch *t*-test to continuous regions, the *p*-values indicate that there is a statistically significant difference between zones 2 and 3 for DVIL, between 2 and 3, and from 5 to 7 for TOP45, between 2 and 3, and from 4 to 6 and between 7 and 8 for TOP35, all zones except between 4 and 5 and 7 and 8 for TOP12, anyone for lightning activity, between 2 and 3 and from 6 to 8 for Zsf, and, again, between 2 and 3, and from 5 to 8 for RNN. Therefore, it seems that not all the regions are statistically significant from their neighbours, but this can be caused by the transition of thunderstorms between the neighbourhood areas in most cases.

3.2. Outliers

Outliers identify the extreme values for a data sample. This identification is very important to determine the limits associated with extreme events. The getOutliers function from the “extremevalues” R package [53] has identified the outliers for the different zonal

samples. The outliers have been detected by checking those that are above the limit where, according to the model distribution, fewer than the limiting observations are expected (given length(y) observations). It is important to note that the analysed values correspond to sets with several samples per day, smoothing the daily value for each zone. Therefore, the maximum value for each day and zone for each field has been selected. This has a deeper impact on those fields of variables that are usually concentrated in relatively small areas associated with deep convection (VIL density, heavy rainfall, TOP45 or lightning activity). Meanwhile, other parameters (mainly TOP35 and TOP12) are less affected by this circumstance. Finally, R2 has been obtained through getOuliers, the same function as the extremevalues package. R-squared value is the ordinary least squares value, considering the squared sum of residuals and considering a normal distribution.

One of the first points of the comparison between the previous Table 1 and the following Table 2, which contains the outlier upper limits, is that in some cases (echo top for 12 dBZ, and the surface and total reflectivity) the outlier is below the third quantile of the sample used. In those cases, the probability of observing extraordinary values is higher than for the rest of the parameters. So, very short-term intensities (reflectivity) and very large vertical development of precipitating systems are more frequent than the other variables: tops associated with mid- and high-intensity reflectivity, lightning activity, or 30 min and daily quantitative precipitation estimation.

Table 2. Same as Table 1, but for the outliers. In parentheses, R-squared values obtained once the outliers have been estimated. Bold values indicate the breakpoints for each variable.

Variable	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Zone 6	Zone 7	Zone 8
TOP45	7.6 (0.96)	8.4 (0.97)	9.1 (0.95)	8.7 (0.94)	8.8 (0.96)	9.3 (0.96)	9.7 (0.96)	8.8 (0.97)
TOP35	9.1 (0.88)	9.1 (0.91)	10.0 (0.94)	9.4 (0.92)	9.9 (0.94)	10.4 (0.94)	10.4 (0.95)	10.0 (0.94)
TOP12	12.8 (0.98)	12.0 (0.98)	12.1 (0.98)	12.1 (0.98)	12.3 (0.98)	12.9 (0.98)	12.6 (0.98)	12.1 (0.97)
XDD	4.5 (0.54)	2.0 (0.19)	2.0 (0.35)	2.0 (0.22)	2.0 (0.32)	2.0 (0.22)	2.0 (0.26)	2.5 (0.12)
RNN	25.5 (0.77)	24.3 (0.77)	26.5 (0.77)	25.7 (0.78)	26.4 (0.79)	29.2 (0.84)	24.8 (0.85)	27.3 (0.84)
RN30	8.4 (0.86)	8.3 (0.87)	10.6 (0.87)	10.1 (0.86)	11.3 (0.85)	13.5 (0.84)	12.0 (0.85)	7.6 (0.87)
DVIL	2.3 (0.89)	1.9 (0.94)	2.4 (0.90)	2.2 (0.89)	2.3 (0.91)	2.1 (0.93)	2.0 (0.93)	2.0 (0.92)
ZSF	45.8 (0.99)	46.2 (0.99)	47.6 (0.99)	47.2 (0.99)	47.7 (0.98)	47.0 (0.99)	46.1 (0.99)	43.9 (0.99)
ZTO	46.8 (0.99)	47.6 (1.00)	48.5 (0.99)	48.6 (0.99)	48.8 (0.99)	49.0 (0.99)	48.1 (0.99)	45.7 (0.97)

Another point of interest resides in the high fitting of the datasets for those three variables (TOP12, ZSF, and ZTO), in comparison to the rest, according to the R-squared value (values inside the parentheses). In those cases, the value exceeds 0.97 in all cases, only comparable with the TOP45 ones (near 0.96). For the rest of the variables, the fit is worse, especially for lightning activity (R^2 between 0.12 and 0.54). The reason for these differences rests in the nature of the variables, as it has been explained before: in the events with deep convection or warm rain, echo top (TOP12) or reflectivity daily fields are more continuous in space; in the rest of the products (mainly lightning activity and VIL density, but also rainfall), the spatial outputs are more discrete, with large areas without data. These discrepancies are less evident in other rainfall types, such as moderate convection or stratiform precipitation [31,43].

Regarding the breaking point, there are many similarities between the two tables, predominating zones 5, 6 and 7 (ZSF, ZTO, DVIL, RN30, RNN, TOP35 and TOP12). This confirms that the highest convective activity occurs in the immediate areas of the most elevated ranges, at altitudes between 500 and 2000 m ASL.

3.3. Monthly Behaviour

The combination of the Mediterranean Sea and the different Catalan ranges plays a principal role in the modulation of the precipitation regime along the different seasons of the year. In this section, the different variables from a monthly point of view are analysed, based on boxplot graphics.

3.3.1. Surface Reflectivity

Figure 6 shows the variation between the different zones regarding the surface reflectivity: meanwhile, for zones 1 to 4 (altitude below 500 m) the variation between months is not evident and only hidden maxima can be detected (June and November in zone 1, October in zone 2, and September in zones 3 and 4). In the opposite case, zones 5 to 8 present a clear maximum for the summer months, mainly for July and August. The maximum is more evident for the highest zones. The same behaviour is observed for total reflectivity (ZTO, not shown).

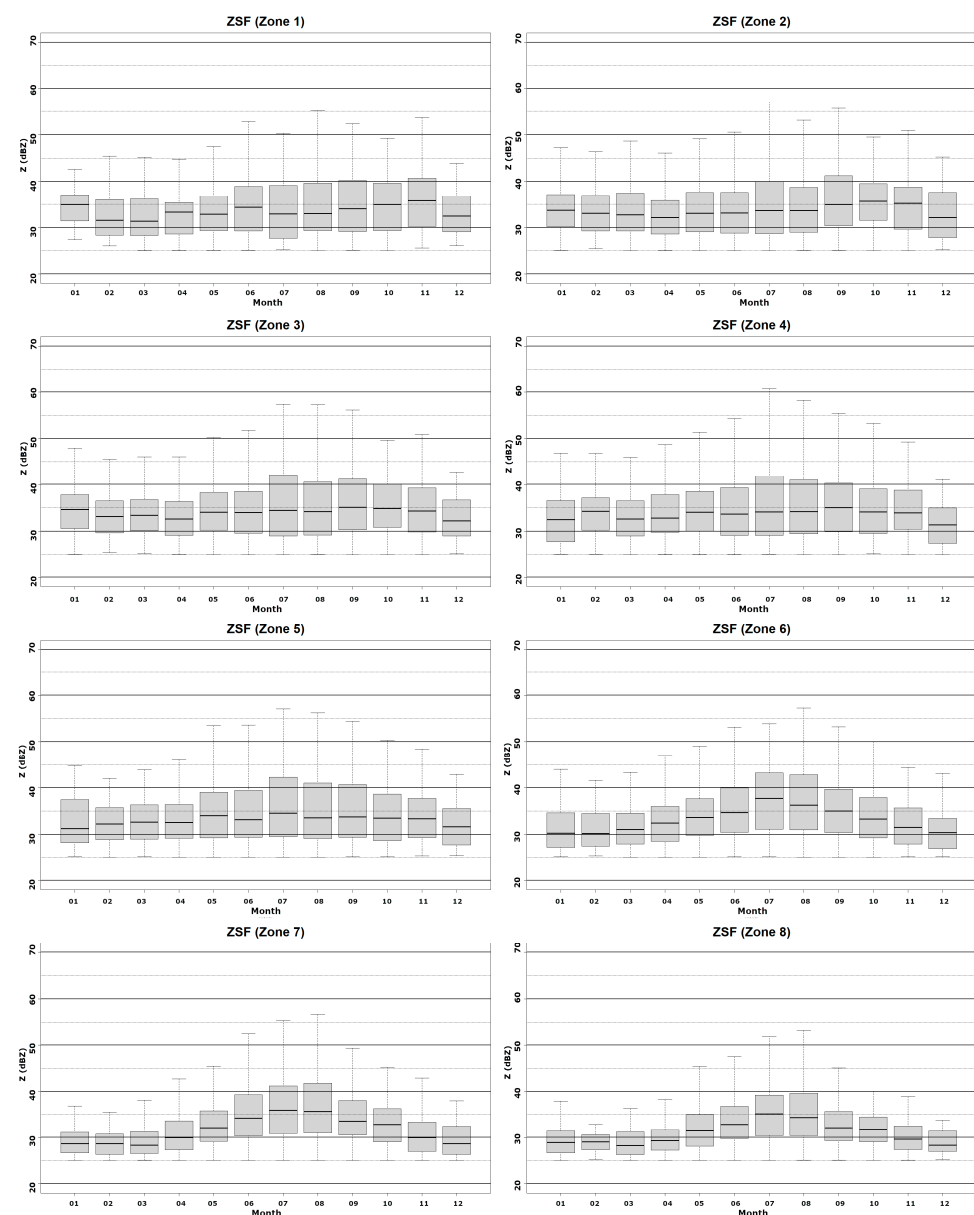


Figure 6. Monthly box plots for the surface reflectivity (ZSF) for the different zones (from 1—top left to 8—bottom right).

3.3.2. Echo Top

Figures 7 and 8 show the evolution of echo top for 12 and 45 dBZ along the year for the different zones, respectively. In the first case, TOP12, there is total agreement between all the regions, with a similar monthly pattern: a maximum between July and August, while the minimum occurs during the period between November and March. This is indicative that deep convection occurrence is more usual during the summer months than in the cold season. In the same line, TOP45 shows the highest values during the same period of the year. This parameter is indicative of the presence of hail, or large hail, especially when values are close to or over 4 km. This threshold is exceeded generally during the warmest period (June to September), and more usually for the more elevated zones (4 to 8).

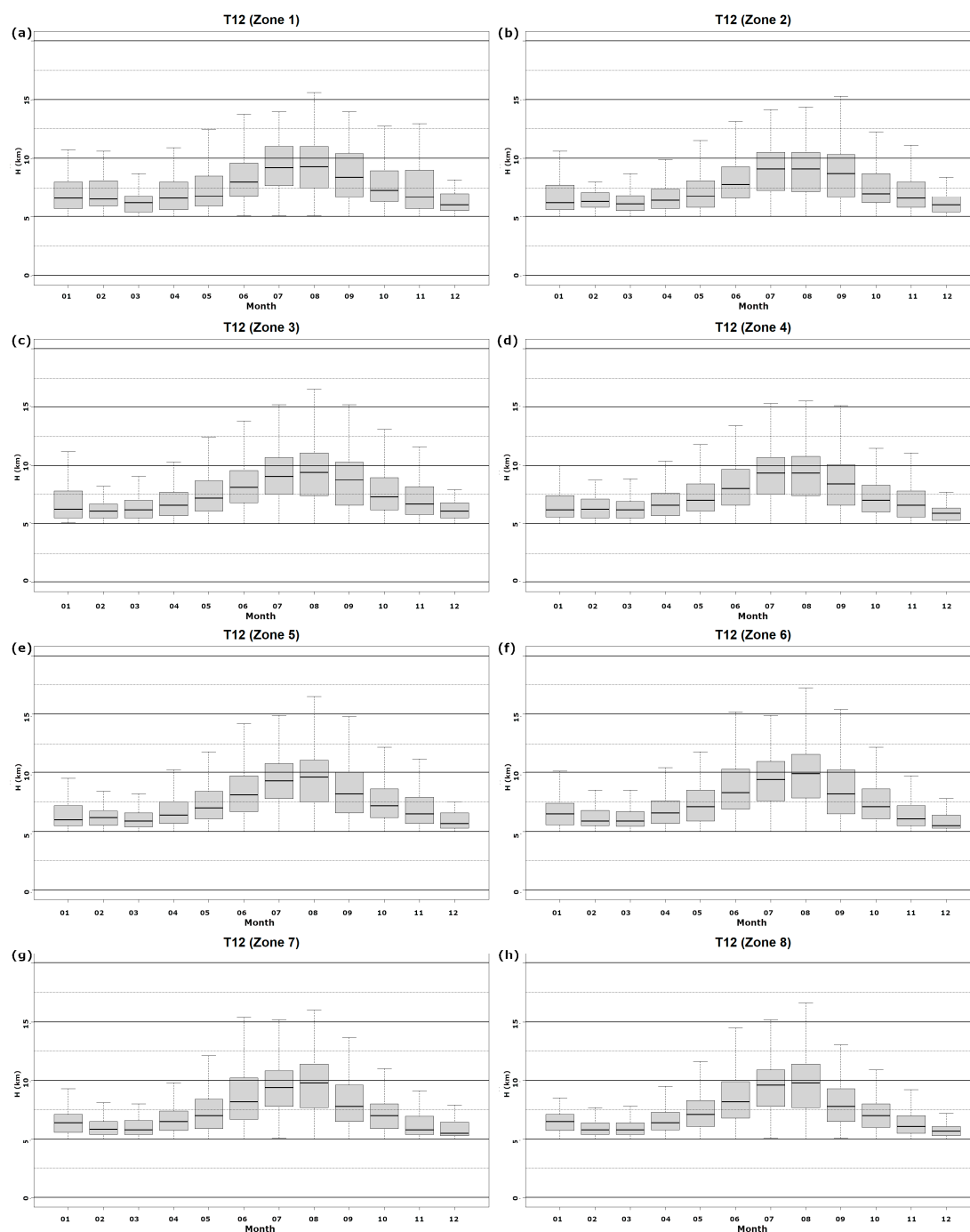


Figure 7. Same as Figure 6, but for T12.

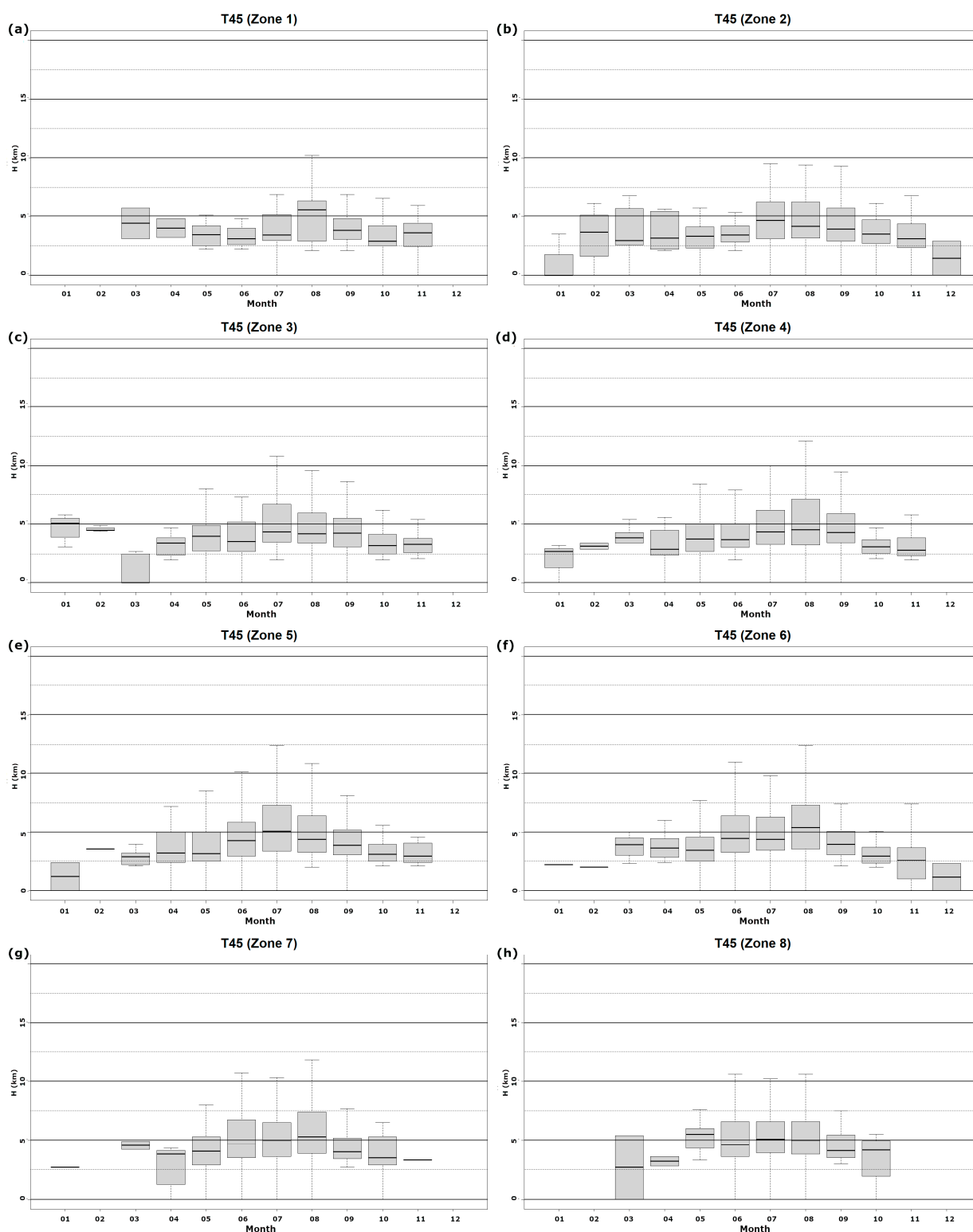


Figure 8. Same as Figure 6, but for T45.

3.3.3. VIL Density

VIL density can be associated with hail occurrence. For instance, values exceeding 2.5 g/m^3 have been revealed as severe hail (diameter over 2 cm) diagnostics in the region of study; meanwhile, 1 g/m^3 is highly correlated with hail of diameter exceeding 0.5 cm (see, for instance, [54]). Figure 9 shows how the probability of hail occurrence in zone 1 is concentrated between August and November. From here, the length of the hail season (this is, with probability of hail occurrence) increases: from April to November (zone 5),

decreasing again from this point, with a new minimum in zone 8 (from May to August). In addition, it can be observed that as the height increases, the influence of the warm season (June to August) is also stronger.

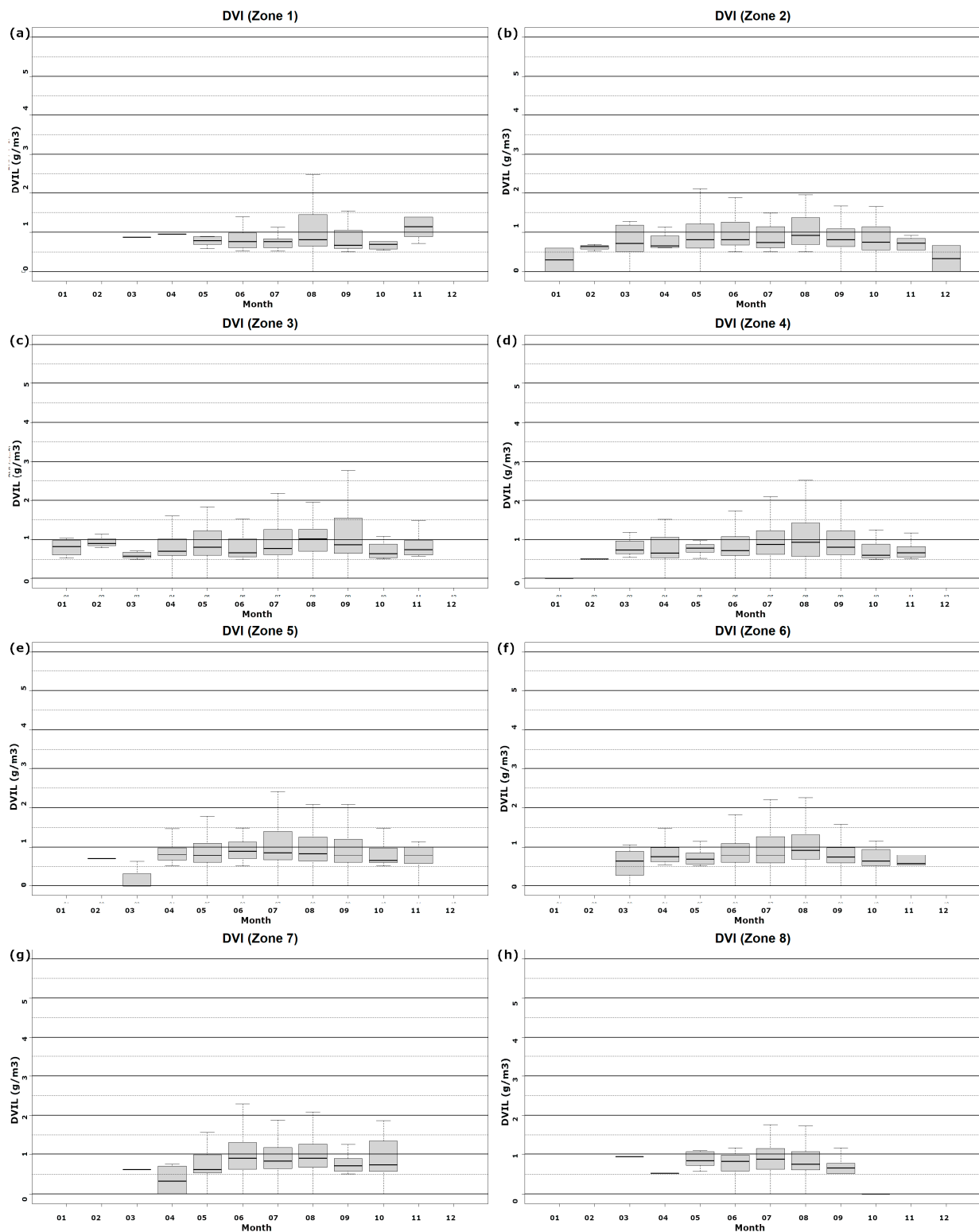


Figure 9. Same as Figure 6, but for DVI.

3.3.4. Quantitative Precipitation Estimation

The last figures of the monthly analysis refer to precipitation estimation, daily (Figure 10) and 30 min (Figure 11). Regarding the first one, the pattern is similar in all

cases, with a bimodal distribution, but with differences depending on the zone (this is, the altitude): zones 1 to 5 show values generally below 5 mm and the peaks in January and November, with very scarce precipitation in the summer months (June to August). Even though the pattern is similar for zones 6 to 8, the maxima shift to February or March on one hand, and October or November on the other hand. In addition, the values are larger for all months.

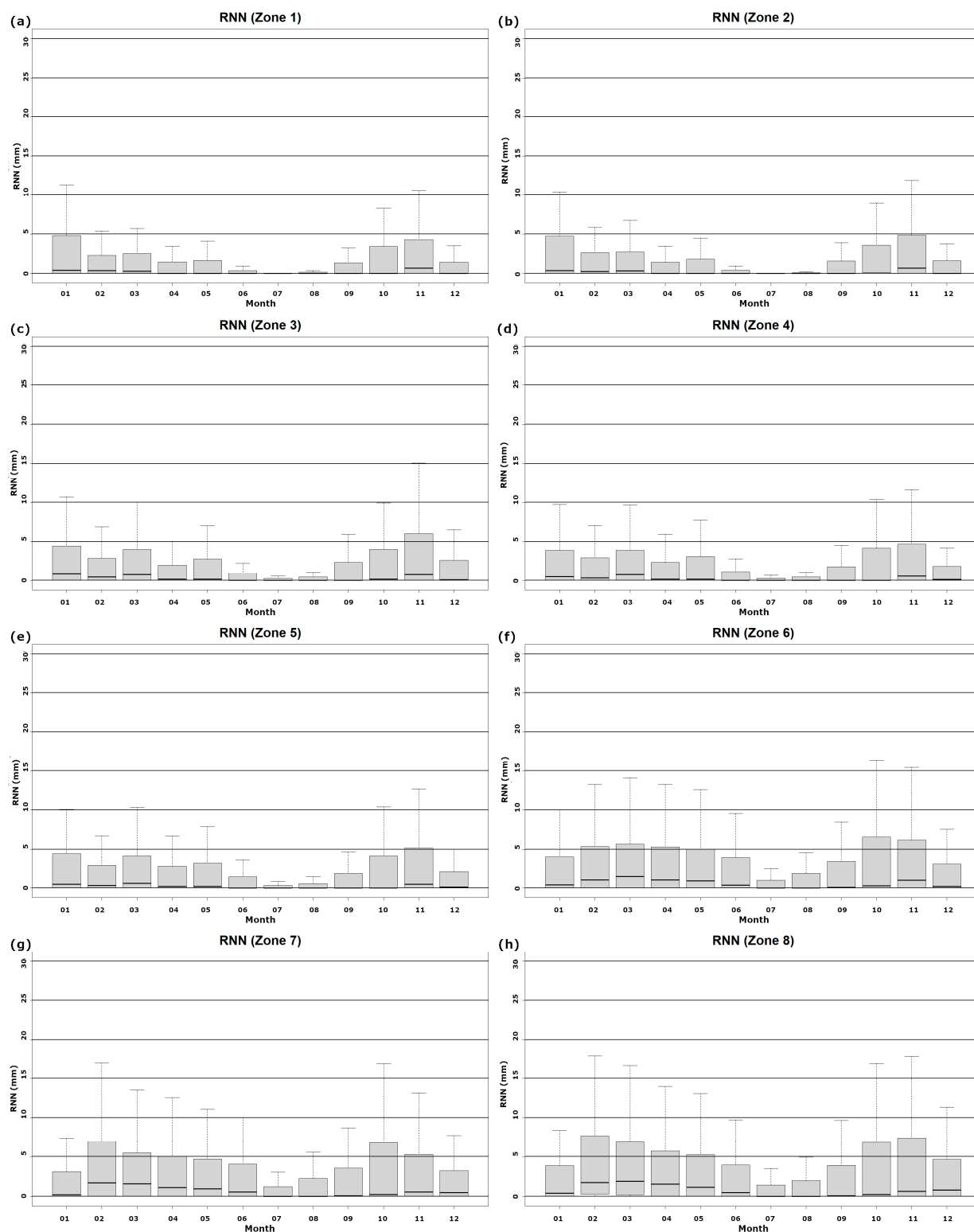


Figure 10. Same as Figure 6, but for RNN.

In the case of 30 min precipitation, which is the cause of flash-floods in many events, the behaviour differs with respect to the daily field. Again, there are two clearly differentiated patterns, with the break point again between zones 5 and 6. While for the zones below 500 m ASL of altitude there are two peaks (in March and September/November, respectively) and the values are below 2.5 mm, in the case of the top zones there is only one maximum, in the summer months (June to August), where the value is over 2.5 mm.

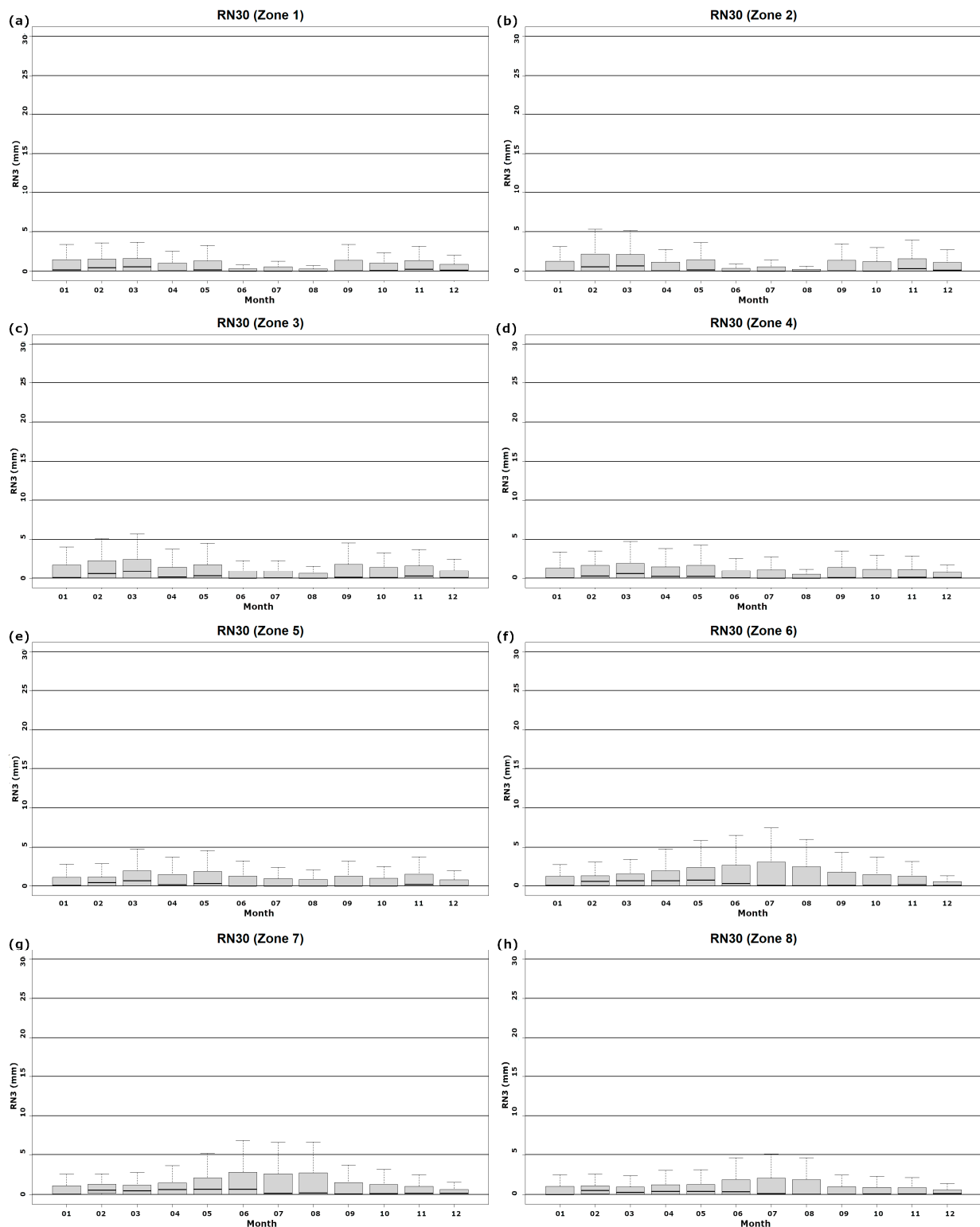


Figure 11. Same as Figure 6, but for RN30.

4. Discussion

The use of a technique based on remote sensing data, rather than automatic weather stations (AWS) as in [27–29,31], has advantages but also limitations. Its main advantage is continuous data at more points than AWS can provide. For instance, the area of Catalonia would be covered by 32,000 synthetic observations with fields of a $1 \times 1 \text{ km}^2$ grid, as used in this study. This is about 100 times more than the maximum number of meteorological stations in the region, fewer than 300. In addition, the time continuity is similar for all points. Therefore, it is not necessary to apply any corrections to make all series comparable. However, there are also limitations. In the case of lightning data, the detection efficiency is the principal cause of the limitations. Therefore, pixels with positive values may be false positives, or conversely, pixels with no lightning activity may be true negatives. In this way, a possible solution should be to consider a validity range for each flash, in which all pixels have a non-null value.

Regarding radar data, the first limitation is that fields are generated considering a constant altitude (except for TOP products). Therefore, it should be necessary to apply corrections to convert the pixel value based on the ground height. However, the complexity of these corrections [55] has led to discarding them for application, because of the large data set. Furthermore, there are many other local or global issues in radar products (ground clutter, topographic beam blockage, electromagnetic interference, among others [56]). Most of these limitations are more evident in orographic areas. However, this handicap has been smoothed here by selecting those pixels less affected by the negative effects. In addition, it is important to bear in mind that the purpose of the study is to evaluate general behaviours, not values at a certain time.

The daily analysis of different points for eight zones with similar heights across several radar fields and lightning data for the period 2016–2025 has revealed important conclusions regarding the yearly precipitation regime associated with sea and topographical influences. Gnann et al. [15] made an extensive review of the factors associated with topography that contribute to the precipitation regime of a mountainous region. Similarly, Schneider et al. [17] demonstrated that low-mountain zones are highly influenced by topography. In the present analysis, from a global perspective, rainfall intensity (reflectivity) and cumulation increased with height up to an altitude that ranges between 100 and 1500 or between 1000 and 2500 m ASL, respectively. Virts et al. [19] showed the discrimination between regions below and over 500 m in the case of thunderstorm activity. Moreover, Tan et al. [20] observed that 1000 m was a breaking point in the precipitation regime of the Southeastern Asian region. Taszarek et al. [49] have demonstrated that lightning activity varies throughout the year, affecting coastal or mountainous regions depending on the season. A similar result was observed in the current study, with maxima in the flattest area (zone 1) and in the upper ranges (zones 6–8).

Taszarek et al. [49] also demonstrated single-mode or bi-modal monthly behaviour, depending on the region, for convection. The analysed variables associated with convection in the present study also showed this variability, with a single mode for ZSF, TOP12, TOP45, or DVIL; meanwhile, for daily cumulated rainfall, a double mode was observed. A case in point is the 30 min cumulated rainfall, which exhibits a bimodal pattern at 500 m and a unimodal pattern at higher altitudes.

Abel et al. [16] showed that precipitation in coastal areas has a high dependence on the elevation gradient of the region and, in addition, how the topography blocks precipitation in some circumstances, allowing high amounts of rainfall in elevated areas, coinciding with Godart et al. [21]. This is coincidental with the current results for the 90th quantile or the outliers analyses, with breakpoints at 1000 and 2000 m, respectively.

Miglietta et al. [9] analysed the influence of the Mediterranean Sea on cyclogenesis, which has a peak in the region of study during the summer and autumn, according to Campins et al. [11]. However, this Mediterranean cyclogenesis is very variable depending on the year (Almazouri et al. [10]), coinciding with the high variability of the Mediterranean precipitation regime associated with the atmospheric conditions that occurred in the region (Dayan et al. [23]). Water conditions have been revealed as one of the main ingredients in the precipitation regime in a coastal region (Caine et al. [26]). All those factors influence the previous results because of the high variability of the weather conditions. However, considering an analysis such as the current one, it is possible to understand better the situations that can lead to a critical scenario, with an excess of precipitation or, on the other hand, with a dramatic drought.

To sum up, this type of Research is important to combine with the results of historical analysis of floods (such as Benito et al. [12]) and of the input of hydrological models (Tramblay et al. [5]; Zoccatelli et al. [6]; Dottori et al. [7]), to avoid or reduce the high impact of floods in the region of study (Hochman et al. [4]; Vinet et al. [8]; Llasat et al. [13]; Stamos and Diakakis [14]). In addition, it is important to bear in mind that droughts and floods are expected to increase in the area of analysis in the future due to climate change because of the meteorological conditions (Granata et al. [2]; Raymond et al. [3]). Furthermore, these conditions are applicable to other regions, such as the Caribbean Sea (Martinez et al. [24]) or South China (Ummerhofer et al. [22]; Peng et al. [25]).

5. Conclusions

Catalonia, like many other Mediterranean Regions, has a climate with a high dependence on atmospheric conditions, but is modulated by the combination of the complex topography and the Mediterranean Sea. These factors make the precipitation regime highly variable and can produce very long dry or wet seasons. Some reports verified by recent observations have indicated that global warming has a major impact on the Mediterranean Basin, with an intensification of droughts and heavy rain, with an increase also of extreme wildfires, floods and flash floods. Therefore, the current analysis intends to give some clues to the current state of the precipitation regime to help with the management of the water resources of the region.

From the study of daily values of different radar and lightning parameters for different altitudes, it has been observed that topography and coastline play a major role in the general behaviour of precipitating events in Catalonia. To sum up, the breakpoint for echo tops (1000–2000 m ASL) indicates that the major vertical developments occur near the peaks of the higher ranges; the lightning activity has the breakpoint in the coast (thunderstorms are more active in the interaction between sea and land); large rainfall values occur over 1000 m ASL, this is, in the highest zones; finally, the higher probability of hail (DVIL) and the higher reflectivity (rainfall intensity) are observed in the inland planes and mid-ranges (between 100 and 1500 m ASL).

The outliers' thresholds can be useful to identify anomalous behaviours of precipitating structures, associated with adverse weather. Therefore, thunderstorms reaching 13 km (TOP12), 10.5 km (TOP35) or 9.8 km (TOP45) are indicative of anomalous vertical developments, while zones with more than four flashes per km² will present a high degree of convective severity (coinciding with the threshold of 2.5 g/km³ of DVIL). Intensities (reflectivity) over 48 dBZ are also unusual values, or 14 mm in 30 min.

Considering the monthly data, it has observed double behaviour: on one hand, a single maximum mode, generally concentrated on warm months for convective parameters (T45, ZSF, DVI or RN30, only for heights over 1000 m). This isolated peak corresponds to the severe convective period in the region (June to August). Observing peaks out of

this season is indicative of anomalies in the convective yearly cycle in the region. On the other hand, a double maxima pattern with peaks near March and November is observed for rainfall variables, mainly. In the case of total rainfall, this double peak is observed in all zones, while for the thirty-minute cumulation the double peak only occurs in zones 1 to 5, indicating that topography modulates the precipitation yearly regime again.

To end, identifying disruptions of this behaviour for a period of three or more months can warn of anomalous atmospheric conditions that can anticipate a long wet or dry period. In addition, these anomalies can be associated with a displacement of the yearly convective regime. For instance, the advancement of the convective peak can negatively influence the agricultural production of the different areas concentrated in the plain zones.

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Abbreviations

The following abbreviations are used in this manuscript:

WMO	World Meteorological Organisation
ASL	Above Sea Level
XDDE	Lightning Location System (Xarxa de Detecció de Descàrregues Elèctriques)
LF	Low Frequency
VHF	Very High Frequency
CG	Cloud-to-Ground flashes
IC	Intra-Cloud flashes
DE	Detection efficiency
XRAD	Catalan weather radar network
ZSF	Reflectivity at the surface
ZTO	Maximum reflectivity value for the complete column
T12, T35, and T45	Echo top (or the maximum height where an echo exceeds a certain reflectivity threshold) for 12 dBZ, 35 dBZ, and 45 dBZ
RNN and R30	Quantitative precipitation estimation at daily and 30 min time resolutions
VIL	Vertically Integrated Liquid
VILD	VIL density

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