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ANALYSIS AND SPATIAL BEHAVIOUR OF THE TEMPORAL FRACTALITY OF PRECIPITATION IN MAINLAND SPAIN AND THE BALEARIC ISLANDS (1997 - 2010)

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I. INTRODUCTION

The variability of the climatic system and its variables is significant at any timescale. Precipitation in the Iberian Peninsula is the variable which exhibits a higher degree of dispersion for both cumulative quantities and temporal distribution, making it an interesting subject matter (Casanueva et al., 2014; Gonzalez-Hidalgo et al., 2009; de Luis et al., 2010; Martin-Vide et al., 2006; Rodriguez-Puebla et al., 2010). The aim of this study is to understand the climatic significance of the fractal dimension applied to precipitation series at a high degree of resolution thus enabling the differentiation of regions based on the homogeneous behaviour of this indicator in the study area.

The enormous interannual variability of total precipitation at the observatories with the longest-running series in the study area is evident when taking the accumulated rainfall from year to year into account (Martin-Vide, 2008). However, this dispersion is recorded not only at a single point year-on-year, but also spatially, and considering the seasonal distribution of precipitation, it is possible to obtain a wide range of seasonal precipitation patterns in Spain (Martín-Vide et al., 1998).

Fractal is a word invented by Benoit Mandelbrot (1976) to associate a class of objects which played a historic role in the development of mathematics during the last third of the twentieth century. This concept is used to refer to objects that are too irregular to be described with traditional geometry but have the important property of being scale-invariant.

There is a direct relationship between the fractal dimension D and the Hurst exponent (Gneiding et al., 2004), and stochastic models expressing this relationship may be presented as follows:

$$D = n + 1 - H$$

In this case, H is the Hurst exponent, and n is the number of dimensions of the considered space (in this case, 1 for temporal series). When the Hurst exponent is less than 0.5, i.e. when the fractal dimension is greater than 1.5, the behaviour of the series is considered to be random.

The fractal analysis has been used successfully to measure irregular linear characteristics, such as the length of the coastline, to characterise landforms and to regionalise spaces according to the landform. Fractal analysis methodology has also been applied to studies of climatic factors for several decades, since some of the variables (temperature, precipitation, atmospheric pressure, etc.) exhibit fractal behaviour, both spatially and temporally, to the point where the persistence of these variables and their interdependencies are determined (Rehman, 2009).

Most applications of fractals in climatological studies have focused on prediction methodologies, as far as models are concerned, and to their validation; however, these principles have not been applied to the purely dynamic behaviour of the climatic system. By the very definition of a fractal object, the application of the Mandelbrot postulates has been directed towards the spatial distribution of precipitation in patterns which would correspond to fractal objects. The question has even been raised as to whether it is actually possible to make a fractal approximation to the precipitation (Sivakumar, 2001). The discovery of these new realities has led to advances in precipitation models that have significantly improved upon the existing models (Chou, 2003), resulting in the simulation of precipitation fields following the multi-fractality property which certifies the scale invariance of this phenomenon. To continue advancing this understanding, it is essential to know whether the temporal distribution of precipitation follows the same principles.

The application of concepts arising from fractal theory is more intuitive for the spatial distribution of precipitation than for its temporal distribution. When speaking of spatial distribution and fractals, the self-similarity almost automatically leads one to think that a field of precipitation may have a fractal form. When speaking of the temporal fractality of precipitation, however, it must be assumed that scaling leads to determine whether rainfall has accumulated within different time intervals for a certain period, and to see if this behaviour is repeated during time intervals of greater and lesser duration. In most studies on scaling properties in the precipitation process, the multifractal behaviour has been investigated without accounting for the various rain-generating mechanisms involved. However, it is known that precipitation processes are related to certain scales determined by climatological characteristics as well as regional and local weather characteristics. One of the implications of these correspondences is the possibility that the multifractal precipitation parameters can depend on the dominant precipitation generation mechanism. Fractal analysis techniques were applied to rainfall data recorded in the Barcelona metropolitan area from 1994 to 2001 as well as a selection of synoptic rainfall events recorded in the same city from 1927 to 1992. This influence was also revealed in the analysis of the effects of seasonality in the multifractal behaviour of rainfall in Barcelona (Rodriguez et al., 2013) and its fractal behaviour in Catalonia (Meseguer-Ruiz et al., 2014). The value of the fractal dimension has been determined as a result of studies carried out in other areas of the Mediterranean region (Ghanmi et al., 2013).

II. DATABASE AND METHODOLOGY

The databases of 48 observatories within the Spanish Meteorological Agency's (AEMet) network of automatic stations from which rainfall data were derived to a 10-minute resolution were used in this study. Seventy-five observatories were initially provided, but those series for which the missing values exceeded 15% were discarded. Those values which appeared as outliers, i.e. those too high to be recorded at 10 minutes were also eliminated in order to maintain the homogeneity of the series to the greatest extent possible. The study area is covered satisfactorily, as shown in Figure 1.

Moreover, a common period between 1997 and 2010 was selected for the observatories in which good homogeneity was obtained.

The fractal dimension (D) was calculated according to the box-counting method, as follows. Based on rainfall records at a 10-minute resolution, the 10-minute period was considered to be the basic unit interval for performing the analysis. Periods containing 1, 2, 3, 6, 12, 18, 24, 36, 48, 72, 144 and 288 unit intervals, i.e. periods of 10, 20 and 30 minutes and 1, 2 , 3, 4, 6, 8, 12, 24 and 48 hours, respectively have been identified below. The number of periods for which some quantity of rainfall has been recorded was also counted. The use of intervals ranging from 10 minutes to two days reflects the intention of studying continuity or the lack thereof at small time scales. The value of the fractal dimension of the temporal distribution of precipitation is defined, based on the slope of the resulting regression line, as representing pairs of values obtained from the natural logarithms of l, the extent or length of the interval in hours, and N, the number of intervals with precipitation. In fact, the logarithms for these pairs of values at each observatory are remarkably well-aligned. The fractal dimension D is given by $1 + \alpha$, where α is the absolute value of the slope of the regression line. The r^2 values of the regression lines used to determine D are very high, both for the full year and at the semester level, with the lowest being 0.9757 at the Ibiza Airport during the six-month summer period.

This process was carried out with an evaluation of the complete series as well as the warm and cold semesters, in such a way that three values were obtained for D at each observatory. By way of illustration, the data from the Avila observatory are shown in Table 1 and Figure 2. Thus, for this case, D values of 1.5, 1.4655 and 1.5228 were obtained for the full year, the warm semester and the cold semester, respectively.

III. RESULTS

The D values were obtained for all the observatories during the above specified period for the year and for the warm and cold semesters (Table 2). For the full year, the values range between 1.4499 at Ibiza Airport and 1.6039 at Lugo Airport, whereas for the warm semester, extreme values occur again at Ibiza Airport (1.4253) and Jaca (1.5404). For the cold semester, the lowest value was recorded once again at Ibiza Airport (1.4600) and the highest at Lugo Airport (1.6388). Table 3 shows the confidence intervals of the fractal dimensions for each case, and it is possible to reject the null hypothesis that the series are random and to determine that the differences observed between the fractal dimensions for warm and cold semesters are significant at 95%. Higher values are always obtained during the cold semester than in the warm semester, although these differences vary in magnitude depending on the observatory. The greatest difference was recorded at Vitoria Airport, where it was 0.1137, while the least was that at Zaragoza Botánico, with a value of 0.0045.

The spatial behaviours of the various D values and of the differences obtained are shown in Figures 3 to 6. A spline interpolation was carried out for the entire study area. This procedure is widely accepted for this type of process in which the variable is neither stationary nor of first or second order. Figure 3 shows the spatial distribution of the variable D for the full year, illustrating how the highest values are concentrated in two areas: in the Cantabrian watershed, with D values in excess of 1.56, and, to a lesser extent, in the southern part of the Guadalquivir Valley. The lowest values are found in the Balearic Islands, in the eastern mainland region, and in the Ebro Valley whose values are between 1.47 and 1.51, plus the western part of the northern sub-plateau in which there is an area of low values close to 1.50.

The distribution of D values during the warm semester (Figure 4) exhibits some similarities with the distribution of D for the full year; the minimum values of between 1.46 and 1.44 occur once again in the Balearic Islands and in the Mediterranean coastal strip, this time extending further south and with less presence in the hinterland. The maximum values of between 1.50 and 1.52 occur in the Cantabrian watershed, but with some values that are markedly lower than those observed for annual precipitation. The D values in the Guadalquivir Valley are not as high, hovering around 1.49. In the western part of the northern sub-plateau, low values of approximately 1.46 continue to appear.

The D values for the cold semester (Figure 5) follow a distribution that is very similar to that for the full year. The highest values of above 1.60 occur in the Cantabrian watershed and Galicia, and the lowest, of less than 1.52, appear in the eastern part of the mainland and in the Balearics. The primary difference is that the values occurring in the Guadalquivir Valley are not as high, hovering around 1.56 and 1.58. The values for the western part of the northern sub-plateau are not as low, being slightly removed from the mainland minimum, between 1.52 and 1.54.

Similarly, it is useful to know the spatial distribution of the differences between the D values from both semesters (Figure 6), since these may be representative of the various mechanisms found at the source of the precipitation from one semester to the next. The patterns in the spatial behaviour of the differences in D values for both semesters are not as obvious as in the above mentioned cases. The Guadalquivir Valley and most of the Cantabrian watershed have been identified as areas where the difference of the cold semester minus that of the warm semester is high, close to or greater than 0.1. In other areas, these differences are attenuated or are virtually non-existent, on the order of 0.004. They occur primarily in the eastern mainland and the interior of Catalonia. Part of the Balearic Islands and some locations in Catalonia and Valencia are exceptions to this, since in the extreme north-east of the former and in the north and interior of the latter, differences appear more pronounced, close to 0.1. In this case, the western sector of the northern sub-plateau, in which both annual and seasonal recorded D values are usually low, presents some seasonal differences which are also moderate, but not to the same extent as in the eastern mainland region, approximately 0.03 and 0.04.

IV. DISCUSSION AND CONCLUSIONS

The values obtained for the fractal dimension D at the 48 observatories studied range between 1.4499 and 1.6039 on an annual basis, between 1.4253 and 1.5404 for the warm semester, and between 1.4600 and 1.6388 for the cold semester. At all the observatories studied, the D value for the warm semester is lower than that obtained for the full year, and the D value for the cold semester is higher than that for the full year.

These D values are not comparable with other published studies for similar study areas (Meseguer-Ruiz et al., 2012; and Meseguer-Ruiz et al., 2014), as the temporal resolutions of the series used are different. A resolution of 30 minutes was used in the aforementioned studies, whereas a 10-minute temporal resolution was used in this study. Consequently, the D data obtained in the other studies are usually lower, as there are no count values for intervals of 10 and 20 minutes. Therefore, when obtaining the corresponding natural logarithms and plotting the regression line, the absolute value of its slope is lower and so, therefore, is the value of D.

Breslin et al. (1999) propose an alternative method to box-counting and Hurst's R/S analysis for calculating the fractal dimension of a precipitation time series based on the variation of monthly precipitation totals. This study affirms the preference for that methodology when calculating the fractal dimension, particularly in cases of monthly data which is not at a 10-minute resolution, due to the large number of consecutive nulls, which would result in null variations and the inapplicability of this methodology.

The D values obtained for Tunisia in Ghanmi et al. (2013) are comparable to those obtained in this study, as they were calculated from precipitation series with 5-minute resolutions using a box-counting method. These values are positioned around 1.44, which makes them very similar to those which have been found in areas with less precipitation on Spain's mainland (Levante, southeast Iberia and the Ebro Valley) and in the Balearic Islands (1.4499 in Ibiza).

The D values are always lower in the warm semester than in the cold semester. It is well known that the rain in the second case is more strongly associated with frontal systems which give rise to preferably stratiform precipitation which is more continuous over time, whereas in the first case, the precipitation has a more convective and concentrated nature. Therefore, low D values of below 1.5 appear to be associated with precipitation of a convective character, while high D values would be linked with rainfall which is more continuous and less concentrated. This is true at a large number of observatories. The D value during the warm semester, however, remains high in the north, and may be associated with precipitation of frontal origin, as is the case in northern areas of the Iberian Peninsula throughout the year.

Comparisons of this indicator are complicated, as no studies, other than that of Meseguer-Ruiz (2014) are known to have presented the spatial behaviour of the fractal dimension of precipitation time series in the Iberian Peninsula. Several patterns of spatial variation in D can certainly be established based on the knowledge of pluviometric behaviour in mainland Spain and the Balearic Islands and as a function of the period studied.

Based on the results obtained, we can state that, on an annual basis, the highest fractal dimensions are in the northern mainland and the Guadalquivir Valley, areas where significant amounts of precipitation are collected during the winter and throughout the entire year in the first region. The lowest D values occur in the eastern Mediterranean coast and in the Ebro Valley, where the rainfall is usually scarce and highly seasonal.

During the warm semester, we can observe the decline of D values in the Guadalquivir Valley, while values remain high in the northern region compared to those occurring in the rest of the study area. During this time of year, frontal systems continue to arrive in the north of the Iberian Peninsula from the west, although less frequently, while in the southern mainland, the Azores High, having drifted northward from its usual position, plays a role in blocking the Atlantic storms, thereby reducing precipitation almost to the point of non-existence in the middle of summer. Low values continue to occur on the eastern Mediterranean coast, as this is a region where summer precipitation is generally scarce. Relatively high values appear in the western Pyrenees region, as major rainfall is recorded during the summer months. In the centre of the mainland, D values remain low, but not as low as in the Mediterranean area.

During the cold semester, we can observe that the highest D values continue to occur in the northern region, and the lowest continue to occur in the Mediterranean region. The second maximum in the study area occurs in the Guadalquivir Valley with relatively abundant precipitation. The principal types of weather associated with precipitation on the Iberian Peninsula and in the Balearic Islands during the cold semester are those involving the passage of frontal systems associated with Atlantic storms. These fronts tend to affect the western part of the mainland, leaving significant precipitation in their wake which decreases as they move eastward. They normally bring scarcely any rainfall to the Mediterranean area. In the Guadalquivir Valley, winter precipitation is associated with storms stalled in the Gulf of Cadiz which bring large amounts of water. However, in many parts of the eastern Mediterranean watershed, the secondary rainfall minimum occurs in the winter, which would explain the low D values with scattered rain over time.

The existing differences between the cold and warm semesters are greatest in the areas in which the D values are highest, regardless of the time of year considered, and are minimal in regions with the lowest fractal dimension. This implies that, between the two periods, there are major differences in the frequency and persistence of rain in regions with higher D values as compared to regions with low D values. This reflects the fact that, during the warm semester, the arrival of frontal systems in the Iberian Peninsula is much less common than during the months of the cold semester.

The uneven spatial distribution of the observatories used may lead to an apparent bias in the results. The absence of any stations in the driest part of the study area (Murcia and

Almeria), and in the south-western mainland (Huelva and Cadiz) may have affected the results. Likewise, if there had been observatories along the northern frontage of the islands of the Balearic Archipelago, it would have been interesting to test whether the D values in these cases were higher than those of Ibiza, Palma, Porreres or Menorca. In this way, the orographic effect and bias involving the irregular distribution of measuring points would have become clear.

The fractal dimension values in temporal series for the Iberian Peninsula and Balearic Islands depend on the location and rainfall readings of the observatory. From the spatial distribution of the fractal dimension, it has been possible to identify four regions; a northern region, where the highest D values occur, both annually and seasonally; a southern region with high values both throughout the year and during the cold semester, but with lower values during the warm semester; a central region on the Inner Plateau, always with relatively low values for the full year as well as for both semesters but with marked differences between them (on the order of 0.06); and a Mediterranean region and the Ebro Valley, with the lowest D values, regardless of the time of year. Lower D values comply, to a greater extent, with the characteristic of self-similarity in the temporal distribution of precipitation, and conversely, higher D values comply less, which coincides with the results presented in Selvi et al. (2011).