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SPATIAL ANALYSIS OF HEAVY RAIN IN MALAGA CITY (SPAIN)

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I. INTRODUCTION, ANTECEDENTS AND OBJECTIVES

Precipitations in Mediterranean climate have high variability in time and space, as a lot of investigations show (Llasat *et al*., 2005; Neppel *et al*., 2007; Rodrigo & Barriendos, 2008). Atmospheric dynamic is also varying during heavy rain (Llasat *et al*., *op cit*.; Martín *et al*., 2006). A lot of areas of Mediterranean regions aren't still well known, although there are fair amount of data. We have used precipitation data of Malaga since 1935.

Systematic comparison of synoptic situations with heavy rains allows us to know which are the types of time that start situations of meteorological risk in concrete locations, as it's obvious that topography introduces modifications in air masses behaviour, especially in Mediterranean areas, where relief overcome frequently thousand meters of height in short tours.

There are a lot of works that have analyzed distribution of Mediterranean climate particularities. There are classic studies of Elias and Ruiz (1979), Font Tullot (1983), Lopez Gomez (1969, 1983), Albentosa (1991) or Capel Molina (2000) about general climate of Iberian peninsula, indexing some particularities of the same one in certain places of the Mediterranean area, especially those in which catastrophic heavy rain is recurrent, in example Levant area of Spain. We obviate the most numerous particular investigations that have been realized on the rains and avenues on Mediterranean coast, especially from Almeria to Barcelona, given that they don't use to have repercussion in Malaga-city, except for some cases, as we could have verified. Mesoscale Convective Systems (Zipser, 1982) depends on different flows in Malaga.

As Capel (1990) indicates «… whenever there happens a disaster of meteorological origin, more than does is a study *a posteriori* of parameters that came together to produce some hydrometeors beyond the common».

Though technologies progress of meteorological analysis thanks to computers every day more powerful drives to remove this idea, obtaining forecasts increasingly trustworthy, it

does not stop being true that accuracy of location of effects that they are foreseen continues being far from our scope. To microclimatic scale, forecasting nowadays is unthinkable. In a region we can be alerted before heavy rains in its area, we can anticipate traffic problems, to be alert of avenues or floods. Nevertheless, prevention in a great city is much more difficult to approach, being difficult to achieve little more than a suitable cleanliness of sewers or fluvial riverbeds that they furrow it.

Specific studies about Malaga-city are sparse but useful. We can quote the book of Elias & Ruiz (1979), about highest rains in Spain where they use several data stations of the city, although is an old work. We can also quote jobs of Senciales (1995, 1997), where they tackle rain intensity in Malaga and its area around. It is also indispensable the work of Capel (1990), that analyzes an especial event of heavy rain in the recent history of the city.

This work tries to tackle and systematize heavy rain analysis that did affect historically to Malaga-city, documented by rainfall registers, to produce probability mapping of events over 100 mm/24 h with certain atmospheric conditions.

II. MATERIALS AND METHODS

2.1. Location

Malaga is located in an intermediate incidence area of processes of Atlantic origin and of those that originate in the Mediterranean, which determines that it does not share with classic characteristics of any of both areas. Neither for this reason, can be generalized in Malaga events that concern the above mentioned areas; not only they do not concern of equal way but in addition it is frequent that numerous events of extreme intensity happened in Malaga spend unnoticed in the Strait or in Levant, for mentioning nearby areas; and vice versa.

Malaga-city relief possesses the peculiarity of to be locating at the foot of a hilly system that reaches 500 m. in only 3 km (Monte San Anton), or 1.000 m in 10 km (La Reina). In the western part there spreads a wide fertile plane (Guadalhorce valley) placed to lee of reliefs as the mountainous country of Ronda, near 2.000 m of height; or Mijas, Alpujata and Blanca, that overcome all of them 1.000 m. That determines a slight föhn effect less than Almeria or Murcia areas, but that demonstrate a decreasing of rainfalls below 500 mm/year at the foot of the valley.

2.2. Methods

The study has been restricted to great intensity events, dealing for such those that overcome 100 mm in 24 hours.

The map of maximum rainfall in 24 hours elaborated by Elias and Ruiz (1979) was assigning to Malaga-city a maximum value of between 220 and 240 mm for a return period of 100 years; and a maximum value of 60 mm/h. for a return period of 10 years. Probabilistic estimations for Malaga-city (Malaga-CASE station) realized by Senciales (1997) indicate a recurrence of between 10 and 25 years for such events; but on having treated a major number of stations, this recurrence seems to be much more short, by what there is approached the study of all the peripheral and internal stations to the city in order to realize a multiple

estimation not based on the only point that could be determined by its location. With these premises a short series of events can be catalogued, simultaneously that we worked with pluviographic and pluviometric records, more extensive the above mentioned in time and in space.

From the criterion absence-presence of the record of a certain event in any point of the city, we use data from 29 internal and peripheral stations of Malaga-city (Figure 1 and 2) since 1935 to 2009; nevertheless, at best we have arranged of data from 15 stations for the same event, being common to possess information of between 10 and 12 of them from 1955. In each one it has been indexed date and volume of any event >100 mm, as well as the quantity registered in moments in which on any other station this fact has taken place. To achieve an identification with sectors of the city we have gathered in crowds depending on its physiographic position in four sectors. It has been considered to be the validity of the series of each one neither of the stations nor the existence or not of lacks in the same one, but, simply, the fact of having registered the event.

From historical files of the web application of Wetterzentrale (2010), with surface information and 500 hPa., between others, we have realized an interpretation and cataloguing of synoptic situation that determined torrential rain, being still the model of Capel (2000), on one hand, and the definitions of Martin Leon (2003) on phenomena of mesoescala.

There has been realized a cartography of recurrence probability of heavy rainfalls applying Poisson probabilistic model as it was used by Senciales and Perles (1994); these results have got in the program Arc-Map 9.3.1 to obtain a distribution map from the coordinates of every value using the application Distance Weighted Spatial Analyst's (IDW).

III. RESULTS

3.1. Tipology of events > 100 mm/24 hours

We have analyzed all the events >100 mm/24 h. recorded in Malaga-city stations since 1950. Along the studied series, events of more than 100 mm are absent in April to August (Table 1). The east type of time (in surface) is in the habit of provoking these situations (Table 2) once added (E + SE + S), but the type of time that prevails is southwest, the same one that frequently generates ordinary rainfalls in Malaga (Senciales, 1995) (Figure 2). It's necessary to add association with great activity frontal systems, frontal occluded systems, cold air flow in height and existence of cut-off lows (Tables 3 and 4). It predominates lightly over the presence of cut-off low in height, though there does not stop being important presence of cold not isolated flow. On having combined it with situation in surface (Table 5) it stands out the fact that the most frequent situation is the presence of heavy rains events simply related to cold flow in height and the arrival of a frontal system, normally of Atlantic origin (Figure 2 and 3). Nevertheless, on having combined it with predominant winds, cut-off low stand out with east (E and SE) and secondarily cold flow with west.

Considering these values, there exists a major frequency of active fronts (occluded or not) with violent rains tied to cold flow that to cut-off lows. Also there is prominent presence of cut-off low tied to depressions, or tied to occluded fronts, effects common both in heavy rains of the peninsular east. This fact is corroborated on having confirmed the type of time in

surface with the trigger phenomenon in surface: front, occluded front or depression (Table 6), that in case of depressions is very tied to east wind in surface.

To attend to distribution and intensity of such events there has been analyzed repercussions that they had in every sector of the city, in order to identify if factor relief affected or not in characteristics of the same ones. Table 7 shows a common reality to all these analyses: high irregularity in the available information. It also reveals that when there is registered an episode of high intensity, the percentage of cases with rains of more than 100 mm (according to number of stations of the zone that registers the event) it is superior in the fertile plane of Guadalhorce (as a whole) to the rest of the area of Malaga-city, and it in spite of the fact that the highest station only comes to 80 m. (Alhaurín de la Torre).

3.2. Multivariant analysis of rains>100 mm/24 hours effects in Malaga

Given topographic characteristics of Malaga city and the location of the stations which we possess, it was tried to group these identifying up to a maximum of five zones: Guadalhorce, urban West, East, Low Mounts (below 300 m.) and High Mounts (> 300 m). In the first tests of linear multivariant correlation with SPSS-18 the following conclusions were obtained: on having analyzed the maximum values for zone, the variables Wind, Height and Month they show slightly satisfactory results (in general, except isolated information, for below even of 0'3); nevertheless, variable situation of surface, sample value of 0'999, 0'921, 0'828, 0'358 and 0'722 with regard to each of five zones, in the mentioned order. Grouped in five zones, therefore, it is wind in surface when they consider to be the average values for zone the variable that more incident shows.

When there are analyzed three zones (Malaga West –fusing Guadalhorce and urban West of Malaga–, Malaga East and Mounts -fusing High and Low), the results are the following ones: values of lower significance than 0'3 when he considers to be the wind in Surface, values of 0'924, 0'909 and 0'341 in situation in height; 0'982, 0'871 and 0'424 in surface situation; and 0'245, 0'926 and 0'018 in the month of the year. The analysis of multivariant relation obtains slightly significant values (0'478, 0'434 and 0'078), being these the highest, which are obtained on having related situation in height and month of the year.

Nevertheless, on having analyzed three zones with the maximum values of every zone, slightly significant values are reached again in Wind (<0'408), shoot in month of the year (0'92 in Malaga East and values of 0'33 in West and 0'033 in Mounts) and interesting in situation in height and in surface. In height values are reached 0'968 in Malaga west, 0'865 in East and 0'15 in Mounts; whereas in surface we obtain values of 1'000 in Malaga west, 0'828 in Malaga East and 0'585 in Mounts. Again, multivariant results are slightly significant: 0'443, 0'503 and 0'061 on having related Height and month of the year (in the rest of the variables the results do not appear).

With four zones, since it gathered in crowds initially and it served for initial production reflected in table 7, the results are less significant. Since it can turn, the complex orography of the Mounts of Malaga is in the habit of giving place to the devaluation of the correlations, whereas Malaga West zone is in the habit of reaching good correlations with numerous variables.

3.3. Recurrence and trend of events > 100 mm/24 hours

The value «percentage of events» of Table 7 shows the probability of which an episode of more than 100 mm is registered in one or more stations of the zone when in any place of Malaga there takes place an event of such characteristics. Of the same table there is deduced that, in 59 years it comes to appear an average of one rain > 100 mm/24 h. every 1.97 years in some point of the city or area of the same one, value different from the recurrence calculated from only one station. Nevertheless, applying the Poisson probabilistic model:

$$P = e^{-\lambda} * \lambda^{x} / x!$$

the recurrence calculated for 30 events of >100 mm/24 h in 59 years is 0'306, or what is the same thing, 1 event every 3'27 years in any point of the studied area. Of 30 registered events, 20 were registered in more than one station simultaneously. Only 10 gave each other in urban area of Malaga, what would involve an average return period of an event >100 mm every 5'9 years in some point of the city. According to the model of Poisson it would be 1 every 7 years.

Only 5 of 30 events can consider to be generalized in most of pluviometric stations. In this case it coincides estimation of recurrence realized for one only station. Poisson's equation would estimate event generalized recurrence in one every 12'8 years.

When we attend to heavy rain events recurrence as a whole for Malaga-city (Figure 5), analysis of accumulated values shows a trend to increasing beyond the linearity that would express a graph of accumulated homogeneous values in a temporary series. There obtains a correlation of $R^2 = 0.9927$ in the polynomial equation:

$$Y = 0.0046x^2 + 0.2055x + 0.9909$$

The result expresses a clear trend to a progressive increase of frequency and number of cases >100 mm. The information is expressive (Table 6): between 1950 and 1979 there were registered in Malaga area 12 events of this type; nevertheless, in the same period of 30 years, from 1980 to 2009, it was registered 18 cases, that is 50% more. Nevertheless, when we attend to the maximum volumes of rainfall of every event >100 mm (Table 7 and Figure 6), despite it doesn't exist a clear model, a trend seems to be given to decrease of the above mentioned volumes, similar (even in its low statistical reliability) to decreasing general trend of annual volumes of rainfall in Malaga-city, estimated by Ruiz Sinoga et al (2010) in 0'57 mm/year.

The trend is also significant to the decrease of torrential widespread events, this is, those in which on very different stations there gather volumes of rainfall >100 mm. Both effects contribute to decrease total rain annual volume in a way as the Mediterranean one, which so much depends on its final volumes of torrential rains.

Table 7 indicates such events, standing out years 1955, 1956, 1978, 1982 and 2004. This definition must be qualified, provided that some other generalized events only were gathered in one or few stations in Malaga-city; it is the case of 1988 or 1989, in that floods were suffered in the Guadalhorce river that, since it is the case of the second one, they managed to affect in Malaga-city.

3.4. Mapping of probability in events > 100 mm/24 hours

To analyze spatially these trends, there have been realized several probability maps of rainfalls >100 mm in the area of Malaga, but here the cases have been segregated punctually and not by zones: every station preserves its own value and does not gather in crowds by zones.

Figure 7.1 shows that maximum values along 59 years have been reached in the north area of the city and, as a whole a major probability of rainfall in the highest areas. For comparison, it can see major frequency in the city that in Guadalhorce valley or Malaga east zone. Figure 7.2 qualifies this information and approaches the probability of which one presents an event >100 mm when meteorological situation unleashes an event of these characteristics; results are similar, though a higher probability is assigned to the area of Airport and in Malaga east zone. Results of both maps contrast with segregation by areas realized in point 3.1 of this work, where Guadalhorce's area was distinguishing as that one in which more events was gathered; information is diluted on having individually analyzed them.

In figures 8.1 and 8.2 it is analyzed if spatial differences exist in events >100 mm/24 h. generated by cut-off low opposite to cold flows. Comparison of both maps shows near probabilities in both cases, though with important shades. As a whole, as the figures were showing 7.1 and 7.2, a major probability of effects seems to be so much of flows as of cut-off low in the coastal area.

Finally, in figures 9.1 and 9.2 probability of effects >100 mm is analyzed with a situation of east wind (east, south-east and south) or of west wind (grouped southwest and west) that generates rainfalls over 100 mm. Results show how east wind is in the habit of concerning more higher zones of the city, reaching its minor probabilities in the own city (excluding north area); nevertheless, they are situations with west wind those who present a major probability both in the city and in Guadalhorce valley, with minimums in some areas of Mounts of Malaga and east area of the city.

IV. DISCUSSION

A lot of pluviometric stations present scanty, incomplete or full of lacks that invalidate them to establish a statistically correct analysis of the rainfalls. Nevertheless, all these stations were adjustments in his day for public services and they took or they continue taking information satisfactorily.

Torrential events use to have random presence in time and in space, but this punctual circumstance can obey topographic reasons which study cannot omit any punctual information that happens, though in statistical series it can only invalidated to know annual rainfall or, enclosedly, the average value of the extreme rainfalls. In fact, in measurements of experimental plots in those who are in use pluviographs installed for the concrete study of the plot, the series lack statistical validity in the immense majority of cases … and nevertheless they are measuring a significant fact: the intensity of the rainfalls.

If we possess a dense (though temporary variable and numerically) network of information before torrential events, we cannot reject it in spite of the fact that his statistical

validity is debatable. The criterion of presence-absence is fundamental in these cases. If a torrential event registers simultaneously on numerous stations (independently of the validity of these) his water repercussion will be more important than if the same one appears isolated, with scanty repercussion on the peripheral stations.

Spatial variability of torrential rainfalls even in limited spaces determines the possibility that such events are more frequent than the stations of measurement indicate us, given that in an area like Malaga city (32 km2 approximately) the number of pluviometric stations of statistically trustworthy and constant series throughout more than 30 years is scanty, and nevertheless, is habitual that some torrential events have been registered in some yes and in others not, or (the most frequent thing) they have not reached significant intensity. And nevertheless, so much some as others have been events of serious repercussions for the urban management.

Besides the preferential location, it is interesting to know temporary trends of rainfalls; for example, in the information here analyzed a certain trend reveals to the increase of the frequency simultaneously that a certain decrease in the volume. Both elements can be of interest for urban management (works of urban collectors, cleanliness of riverbeds).

With these premises, to know the atmospheric situation that determines the criteria of absence-presence in relation with the topography can be a line that we try to establish in this study, being obviously necessary to go deeply into the precise paper of the factors altitude - exhibition.

V. CONCLUSIONS

Frequency of events over 100 mm in 24 hours is higher than analyses of an alone station manage shows or foresees by means of probabilistic analysis. Throughout 59 years there have happened 30 events of this nature in some point of Malaga-city or peripheral area, which would imply a joint approximate recurrence of an event every 2 years. The analysis of the series reveals how this frequency tends to hasten in the last years, though the maximum volume tends to be lightly lower: this one would be one of the keys of decrease of mean annual rains, if we think that share of annual volume of Mediterranean rainfall depends on precipitated quantities in events of great intensity.

Cartographic analyses show how the urban area of Malaga is especially sensitive to these events, with a high probability that reaches major values with cut-off low and west wind flows.

From the analysis of widespread events that have provoked floods in Malaga-city or its area it is clear that three standard situations exist that they are in the habit of giving place to it:

1. Cut-off low associated with depression on Africa (and an anticyclone in British islands), that introduces east wind. Between the events of special intensity, this is the model who more commonly generalized, and for this reason, uses to produce major devastations on Malaga-city.
2. Cut-off low associated with depression in Gulf of Cadiz-San Vicente, though, in a secondary way, if depression is very deep, they also can concern placed opposite to Galicia. In these cases of Atlantic tempest one can give west wind (it is responsible

of frequent rain or of low intensity in Malaga), though the evolution of depression towards Malaga-city uses to giving place to which the wind veers round to east west along the event.

3. Flow in height without defined cold cell is in the habit of provoking with minor frequency generalized events on Malaga-city, but they use to be associated to events more or less isolated of great intensity.

The analysis of the effects on the area of Malaga-city reveals that they don't use to affect equally with east wind situations that those of west wind. The urban center is more sensitive to west situations, while the high zones (Mounts of Malaga, Mijas's Saw) are more sensitive to the east. There is also deduced that cut-off low concern a major proportion of urban zone that heavy rain events with cold flow (without defined cut-off low). With torrential events, the nearest zone to the coast and to the oriental area of Mounts of Malaga is more inclined to events that overcome 100 mm, which, when recurrence is analyzed of these isolated happens (probability of which they overcome 100 mm with an event that overcomes 100 mm in any place of the city), giving special weight to the zone of airport, north of the city and oriental area of Mounts of Malaga.

To consider this fact performs supreme importance for urban management in the one that does not matter in what point of the city it happens, but, simply that happens. Thinking that network of urban pluviometers is neither too dense nor constant for a city over 60 km^2, it is very possible that probability of intense rainfall in some point of the city is higher than calculated from available stations. To attend to synoptic situation can serve to know, depending on presented maps, which are the areas of major probability of torrential rain.