ANALYSING SPATIAL DISTRIBUTION OF CLOUD-TO-GROUND LIGHTNING IN PORTUGAL: PATTERNS IDENTIFICATION AND RELATIONSHIP WITH GEOGRAPHICAL FACTORS

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I. INTRODUCTION

Several studies have been carried out in order to analyse the influence of surface features and geographical factors on lightning activity. The surface features analysed include air surface temperatures (e.g. Pinto and Pinto, 2008), sea surface temperatures (e.g. Altaratz et al, 2003; Tinmaker et al, 2010), elevation parameters (e.g. Dissing and Verbyla, 2003; Neuwirth et al, 2012), lake-effects (e.g. Steiger et al, 2009), land use (e.g. Rozoff et al, 2003), type of vegetation (e.g. Carleton et al, 2008), fire scars (Kilinc and Beringer, 2007), among others. Linear regression models, including bivariate or multivariate analysis, have been the most common approach to investigate the relationship between geographical and terrain variables and lightning activity, namely the density of cloud-to-ground discharges (CGD).

The present study is focused on the analysis of the relationship between patterns of CGD densities in Portugal and a set of geographical variables, more precisely continentality (distance to ocean), topographic features (e.g. elevation and slope aspect) and terrain parameters (e.g. land use and geological units). Analysis of annual and monthly scales will be performed in order to investigate how these relationships behave and change along the seasons of the year. In this sense, three geographical approaches were used for the mainland Portugal: the whole territory, the north sector and the south sector; the last two were divided by the Tagus river, which crosses Portugal from east to west, splitting the country into two different mainland parts with very different terrain characteristics (Fig. 1).

II. DATA AND METHODS

This study was carried out using different datasets encompassing information on lightning activity and geographical features of Portugal mainland territory. With regard to lightning activity, only data of cloud-to-ground discharges (CGD) were used, covering a period of seven years (2003-2009). These data were collected by the Portuguese lightning detection network (cf. Santos et al., 2012), which is maintained by the National Weather Service (Instituto Português do Mar e da Atmosfera; IPMA), consisting in four IMPACT 141 T-ESP sensors (Carvalho et al., 2003; Ramos et al., 2007). According to Rodrigues et al., (2010), this network allows a detection efficiency of about 90% for CGD with intensities higher than 5 kA. Additional details about this network and its corresponding sensors can be found in Santos et al. (2012).

In the present study, five factors were analysed and compared with the annual and monthly spatial distribution of CGD (2003-2009) for the three geographic units:

- Elevation, divided in 9 classes (Fig. 1);
- Aspect, classified in 4-point directions (a 8-point direction map was also used, but no difference was found in the results);
- Distance to the ocean, from the west shoreline, divided in 8 classes (Fig. 1); an analysis using the distance to the ocean integrating the south shoreline was also performed but no significant differences were found in the results;
- Geology, grouped in 9 main geological formations (plus the water bodies);
- Land use, simplified in 6 main types (urban areas, aquatic areas and wetlands, areas without or with sparse vegetation, pastures and temporary crops, open forests and permanent crops and forests).

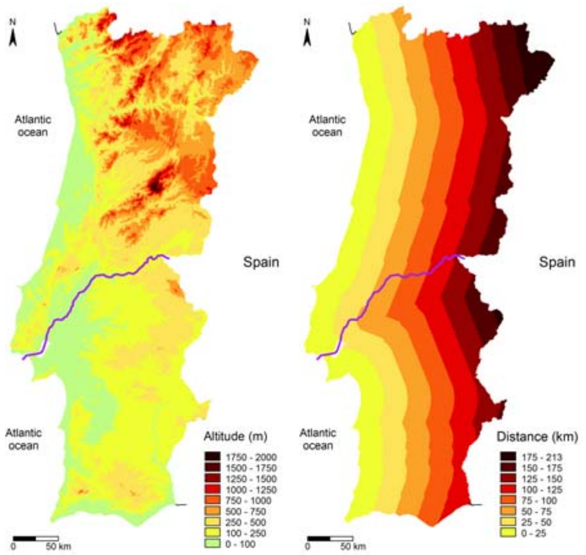

FIG. 1: Spatial distribution of Elevation (on the left) and Distance to Atlantic Ocean from the western shoreline (on the right); the purple line represents the division between "north" and "south" by Tagus river.

Both elevation and aspect maps were generated from the SRTM (Shuttle Radar Topography Mission; NGA and NASA; resolution of about 90m). The geological formations were extracted from the Geologic Map of Portugal, 1/500000 scale (from LNEG/INETI); the land use was based on the Corine Land Cover information (CLC, 2006), 1/100000 scale. Both geological and land use were simplified in respect to shape and size parameters (linear and small features were dissolved in the surrounding ones). Thereafter, all the spatial variables were split in two parts – North and South –, having Tagus river as a natural limit.

The geographical data integration and analysis followed the methodology presented below:

- Calculation of total annual and monthly CGD density (number of occurrences per square kilometre), of the seven years period (2003-2009), with total of 13 maps;
- Crossing between the CGD density and each one of the spatial variables, for the three geographical units – all Portugal mainland, north and south –, for annual data (21 cross tables) and for monthly data (144 cross tables; this task was not performed for “distance from west and south shoreline” and “aspect”);
- Calculation of the CGD density (D_{CGD}) for every class and geographical factor, which can be interpreted as a measure of conditional probability of finding CGD associated to each class; this variable can be calculated by the following formula:

$$D_{CGD} = \sum_{i}^{n} CGD_{i(class)} \Big/ Class\_Area \; ;$$

- Interpretation of results and definition of the functions that characterize the relation between CGD density and the quantitative geographical factors (“elevation” and “distance to west shoreline”), for annual and monthly distributions;
- Analysis based on the Multiple Linear Regression (MLR) for the annual data, using the factors that best represent the spatial distribution of CGD;
- Interpretation of the relations between the monthly CGD densities and the distribution of geographical factors, followed by the identification of the tendency patterns along the year.

All the spatial analysis were carried out using the software ILWIS 3.3 Academic, in a raster structure GIS environment, based on a resolution of 100 m (cell area of 1 hectare).

III. RESULTS AND CONCLUSIONS

The annual CGD density distribution is clearly affected by the relief, in particular by altitude. As shown in Fig. 2 (green bars), this factor can explain about 90% (r^2=0.91) of the spatial variation of the CGD. The importance of this factor increases when only the north sector (Fig. 2), much more mountainous, is considered (r^2=0.95); on the contrary, the distribution of annual CGD densities appears to be much less dependent on altitude in south sector of Portugal (r^2=0.60).

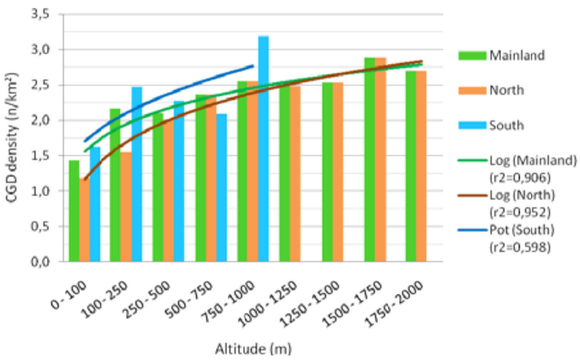

FIG. 2: Relation between annual CGD densities (number per km^2) (2003-2009) and altitude, for the mainland Portugal and for its north and south sectors.

In the same sense, the annual CGD density distribution seems to be affected by the distance to Atlantic Ocean (continentality), although with less intensity as by the altitude. As shown in Fig. 3, this factor explains 85% (r^2=0.85) of the variation of the CGD spatial distribution. However, as expected, this factor is less important in the north sector (Fig. 3), where the influence of altitude prevails (r^2=0.81); on the contrary, the importance of this factor in the south sector, becomes higher when compared with the altitude (r^2=0.69).

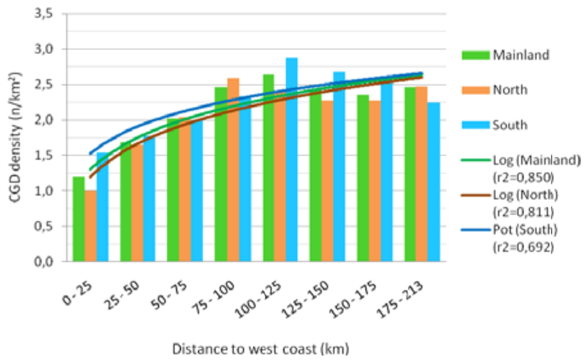

FIG. 3: Relation between annual CGD densities (number per km^2) (2003-2009) and distance to Atlantic Ocean (west coast), for the mainland Portugal and for its north and south sectors.

From the previous results it is expected that both factors can be combined to achieve a better explanation of the annual CGD densities distribution. In fact, the use of Multiple Linear Regression (MLR) explains 99% (r^2=0.989) of the annual distribution in the period of analysis; the expression is as it follows:

$$CGD\left(n/km^2\right) = 1.1298 - 0.00062 \times Elev + 0.0145 \times DistOcean$$

where *CGD* is the expected cloud-to-ground discharge density (in number of occurrences per square kilometre), “*Elev*” is the elevation (in meters) and “*DistOcean*” is the distance from the westhern shoreline (in km). As expected, this formula works better for the northern than for the southern sector, since the behavior of the former one is much more consistent with the behavior of the entire mainland Portugal than the last one.

The observation of the monthly CGD distribution makes clear that these two factors act differentially along the year. As shown in Fig. 4, the frequency of CGD presents strong diferences along the year. The period from December to March has very low densities of CGD, always below 0.1 occurrences per square kilometer; the highest density occurs in September for all territory.

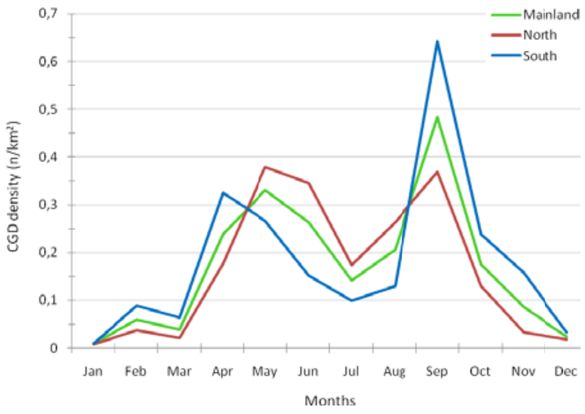

FIG. 4: Monthly regime of the CGD density (2003-2009) in mainland Portugal and for its north and south sectors.

Fig. 5 shows several groups of months, when the coefficient of correlation is considered for both altitude and distance to west coast factors. In general, the CGD density presents high (negative or positive) correlation values with one or both of the factors. From October to February the CGD density shows a strong and negative relation with distance to the west coast, since all the values are between -0.7 and -0.99, which means that the CGD occurs mainly along the coastal areas; during this period, the altitude has no influence in January and just a median importance in the remaining months, with correlation value of about 0.5 in October and between -0.5 and -0.7 in November, December and February.

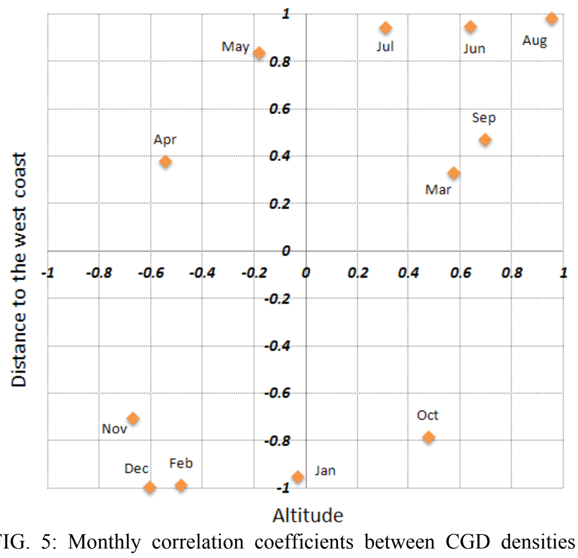

FIG. 5: Monthly correlation coefficients between CGD densities and altitude and distance to west coast in mainland Portugal.

From March to September, the monthly values have the opposite behavior, since all of them presents a positive correlation between CGD density and distance to the west coast; from these, June, July and August can be explained almost completely by this factor (R>0.95), although the latter also have a very strong correlation with altitude; May as no correlation with the altitude but only with distance to the west coast. It is interesting to note that the months with smaller correlation with both factors belong to spring (March and April) and autumn (September and October). The months of winter and summer have a very strong correlation with at least one of the factors.

Given the results described above it becomes clear that different months have distinct behaviors and are influenced in different degrees by the altitude and distance to the western coast. This contrasted behavior is also shown by the differences between the northern and the southern sectors of the Portuguese mainland.

In relation to altitude, January has exhibit a complex behaviour over the mainland Portugal and north sector: the CGD density decreases from sea level to 500 m and stabilizes in the low values until 1000 m, where a notable increasing occurs until 1500 m (there is no occurrences above this altitude; Lopes et al, 2011); in general, this behavior is already detected in December and continues until February (in this case, with occurrences above 1500 m). At first sight, the south sector seems to have a very different behavior, but for the same range of altitudes (the value above 1000 m in this sector are only residual), the same tendency can be observed. March sets the end of this pattern and April brings new characteristics: there is not a clear tendency over the mainland Portugal and north sector, although the higher values of CGD density are concentrated in the lower altitudes, especially from 100 to 500 m. By the contrary, the south sector presents an increasing CGD density, but inconstant, with the altitude. From April onwards there is a tendency for higher values of CGD density occur with increasing altitudes; this pattern is most representative in August, where the relation with the altitude is almost perfect, especially in mainland Portugal and north sector, but also in the south sector. From this month ahead this pattern tends to disappear and gives place to one described for winter months.

In relation to the distance to the west coast, results follows approximately the same evolution along the year as described for the altitude, but the behavior is simplest, with just a few particularities. In this case a general trend to decreasing CGD density with larger distances to the ocean can be observed from October to February (with the exception of the south sector). In March, a month with no specific patterns, the previous one disappears and is replaced, in April, by the inverse trend, especially in the south sector. This incipient decreasing trend, that can be observed in the mainland Portugal and in the north sector, is much more perceptible in the south sector. It extends until May when becomes more evident, especcially from this month on. September, just like March (and April in mainland Portugal and north sector), is a period of transition. Although the relations between annual CGD occurrences, altitude and distance to west coast are obvious, and relatively clear for the mainland Portugal, deep differences can be found from north and south sectors. The northern half of mainland Portugal follows very closely the behavior of the whole territory, when these two factors are used for explain the distribution of CGD density. This means that the function that describe the general annual (such as the hypothetical monthly functions) for the mainland Portugal fits best the behavior of the north sector, than the adjustment to the south sector.

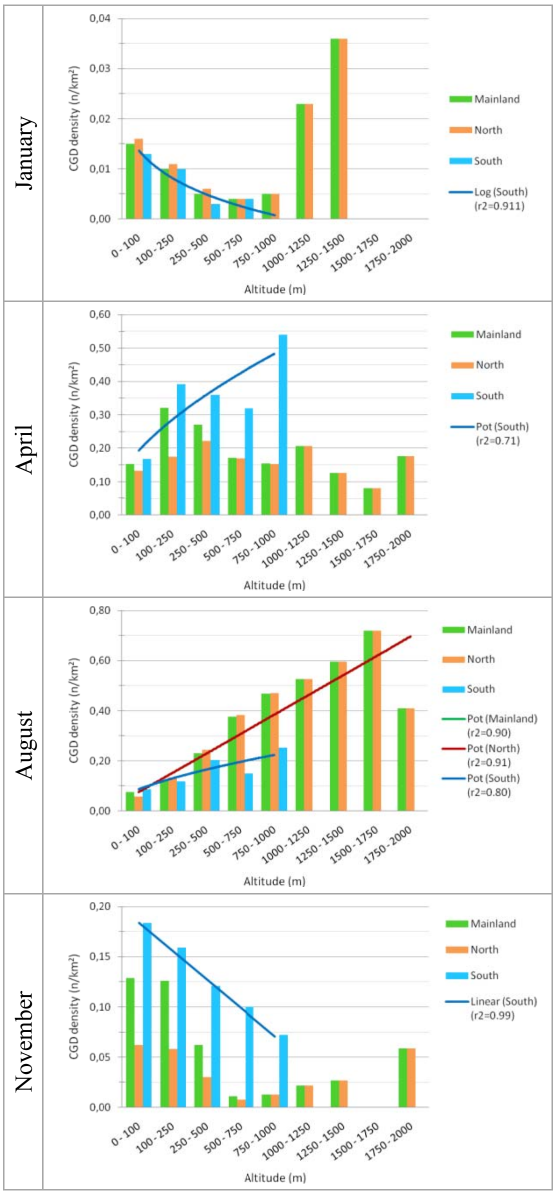

FIG. 5: Relation between annual CGD densities (number per km²) (2003-2009) and altitude, for the mainland Portugal and for its north and south sectors, in some representative months.

From the results obtained through the calculation of CGD density for each class of the five factors, some conclusions were found:

- The slope aspect has no influence, at least in this scale, in the spatial distribution of the CGD in mainland Portugal;
- Is was not found any clear evidence of the influence of the geology and land use factors; nevertheless, in this regard, more research is needed since some residual importance may be expected, especially in the warmest period of the year, when strong sunshine could promote the surface heating, triggering instability and local convection; in some specific cases, it seems that a strong relation between the CGD density and the Normalized Difference Vegetation Index (NDVI) exists, as showned by Lopes at al. (2011);
- The annual and monthly CGD density distribution have a very strong relation with the elevation and distance to Atlantic Ocean (measured from western shoreline); for this reason, the analysis carried out in this abstract is focused on the relation between these two factors and the spatial distribution of CGD.

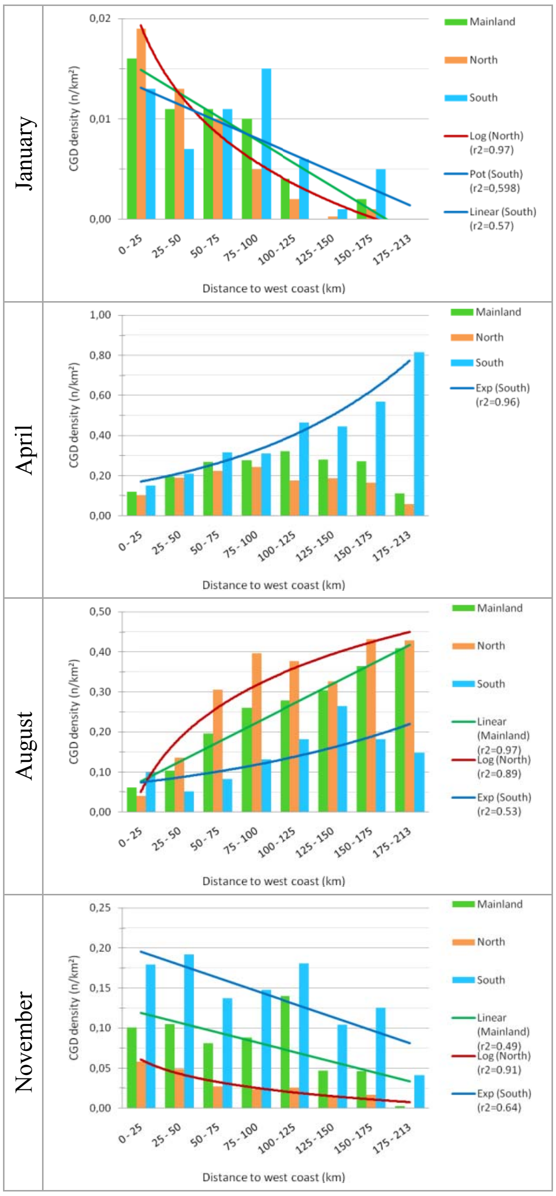

FIG. 6: Relation between annual CGD densities (number per km²) (2003-2009) and distance to Atlantic Ocean, for the mainland Portugal and for its north and south sectors, in some representative months.

The analysis of the influence of these geographical factors on the observed CGD densities should continue taking into account the different large-scale and synoptic atmospheric controls of lightning activity over the region. As it was demonstrated by Santos et al (2012), quite different atmospheric regimes prevails during wintertime and summertime periods of the year, promoting specific dynamical conditions, with possible implications on the role of surface conditions on lightning activity.

IV. ACKNOWLEDGMENTS

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