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Lightning activity over large cities located in mountainous tropical zones and its relationship with particulate matter PM_{10} distribution- the Bogotá City Case.

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Análisis de la actividad de rayos sobre grandes ciudades localizadas en zona montañosa tropical y su relación con la distribución de material particulado PM_{10}. Caso Bogotá.

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ABSTRACT: This paper presents an analysis on the influence of anthropogenic phenomena over the lightning activity in large cities located in mountainous region of tropical zone, specifically in Bogotá City. Some preliminary results show an increase of lightning activity between 33% and 340% for the period under study (2007–2012), when a comparison between urban and rural adjacent zone is carried out. An additional analysis of the influence of pollution on lightning activity was also carried out; this analysis shows that there is a tendency of correlation between number of strokes and particulate matter (PM_{10}) for the zones under study with the highest levels of contamination of the city. In order to achieve the goals of this study, data from one of the Colombian Lightning Location Systems (SID) and the monitoring network of air quality of Bogotá were used. The results are consistent with other studies carried out in different cities of the world.

RESUMEN: El siguiente estudio realiza un análisis sobre la influencia de fenómenos antropogénicos en la actividad de rayos para la ciudad de Bogotá. Los resultados muestran que hay un incremento en la actividad de rayos entre el 33%-340% para el periodo de 2007–2012, cuando se compara la zona urbana de Bogotá con una zona rural adyacente. También se realizó un análisis para observar la influencia de la polución de la ciudad, sobre los rayos. Los resultados muestran que hay una tendencia entre el número de rayos y el material particulado para las zonas con mayores niveles de contaminación de la ciudad. Para realizar el estudio fueron utilizados los datos de la red de localización de rayos - SID y para la información de niveles de polución se utiliza la red de monitoreo de calidad del aire de Bogotá. Los resultados son consistentes con otros estudios llevados a cabo en otras ciudades del mundo.

1. Introduction

Lighting activity study on large urban centres and its relation with anthropogenic activity has as its main goal to observe if phenomena like pollution and heat island can affect such activity. Air pollution is defined as the increase of one or several substances over the normal levels as a result of anthropogenic activity. The increase of such levels modifies the aerosols volume present in the atmosphere that is fundamental for cloud formation [1].

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Urban heat island is a phenomenon that is present mainly in large populated centres and is produced by canalization of rivers, replacement of large extension of lands for roads and the use of a huge amount of concrete, among others. The materials used for the construction of such infrastructure retain heat during the day affecting the gradient of temperature of the city and its surroundings [2].

One of the first studies on the variation of lightning activity over the cities was developed in the Unites States of America in 1995 [3]. The results of Westcott showed an increase of the lightning activity over the cities under study when those results were compared to the ones of the surrounding regions. Since that time, different studies have been carried out in different places of the world observing the influence

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of pollution and urban heat island over the lightning activity [4-12].

Increasing the pollution level affects the microphysics of the clouds because such an increase can modify the amount of Cloud Condensation Nuclei (CCN) [13], generating an increase of the amount of smaller cloud droplet inside the cloud and, at the same time, the coalescence process starts to be slower in order to create raindrops or hydrometeors [14] affecting also the lightning activity [15, 16] due to an increase of the amount of aerosols in the atmosphere.

Naccarato *et al*. [8] concluded that the increase of lightning activity over large cities depends basically on two anthropogenic aspects: Thermodynamic effect and aerosols. Thermodynamic effect is associated to urban heat island phenomenon present on cities that can affect convection process for the formation of thunderclouds. Aerosols affect the cloud electrification process by increasing the lightning activity.

Bogotá is one of the largest cities in South America. It has about 9 million inhabitants, located at 2,625 meters over the sea level; it is divided into 20 different regions or "*localidades*" with only one being rural and the other 19 being urban ones. The urban zones have an extension of 400 km^2 and it is one of the cities with the highest levels of pollution in Colombia, specially related to concentration of PM_{10} [17-19]. Additionally, Bogotá City has a heat island of about 3 °C in relation with its rural zone [2, 20].

In order to avoid confusions generated by the reason that Colombia has been reported as a Country with some of the places with the highest lightning activity in the world (hot spots) [21-23], it is important to remark that even if this is true, Bogotá is a place with very low values of lighting activity but a very good place to develop the present study due to its anthropogenic and geographic conditions.

The present paper analyses and compares the lightning activity over Bogotá City with an adjacent rural zone of similar altitude. Additionally, it intends to analyze lightning spatial distribution over the city and compare it with particulate matter PM_{10} distribution. This study was carried out using data from one of the Lightning Location System (LLS) of the country – SID that belongs to Intercolombia S.A. E.S.P. the largest electric transmission company of Colombia. Pollution data were obtained from RMCAB, it is the Air Quality Monitoring Network of Bogotá and belongs to the municipality of Bogotá. This study was carried out for the period of 2007 to 2012.

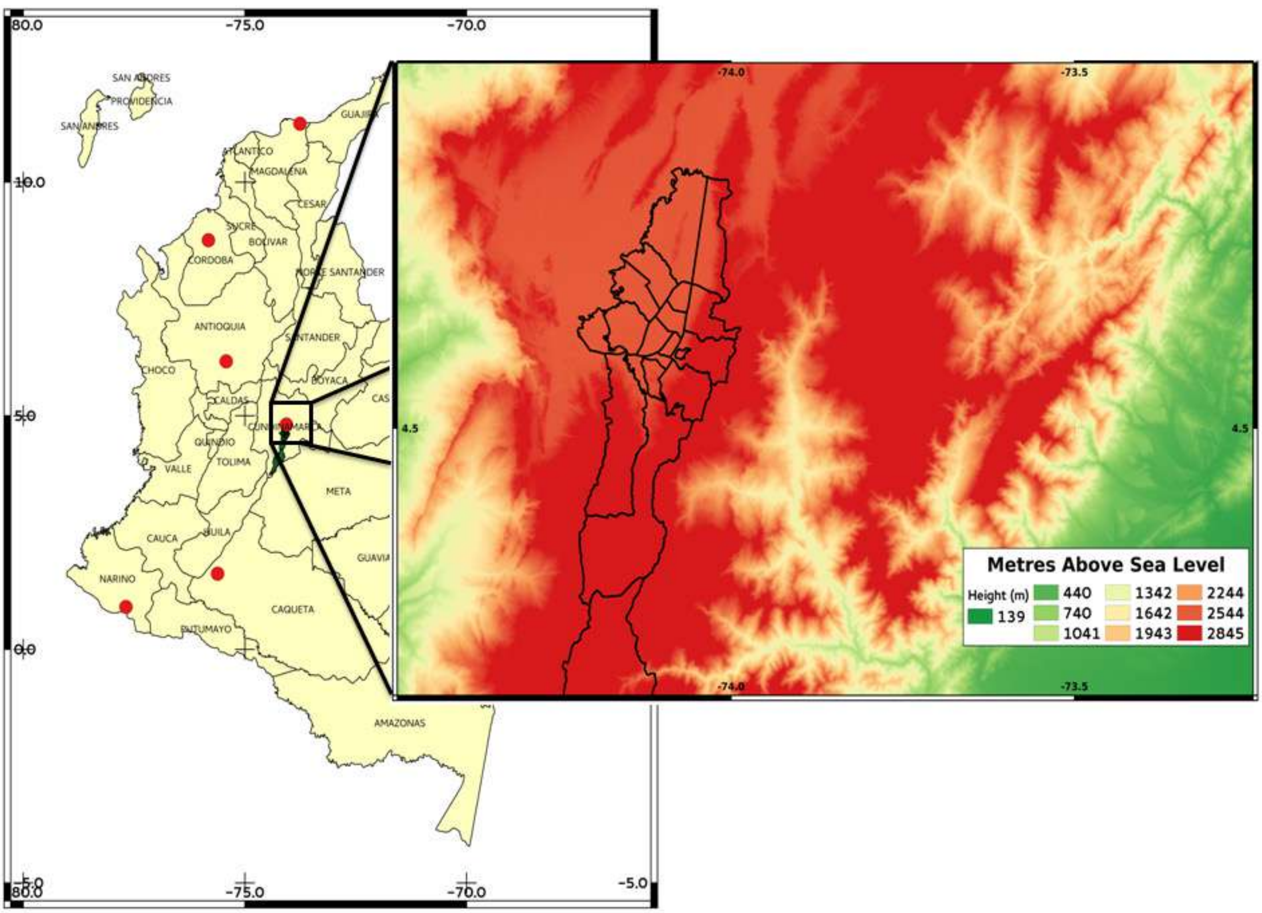


Figure 1 **Geographical location of the Lightning Location System - SID and the elevation of Bogotá City**

2. Data and methodology

As it was mentioned before, this study uses two sets of data. SID data come from a network manufactured by VAISALA Inc and it is composed by six LS7000 sensors located in different airports of the country. The manufacturer specifies that the sensors have a bandwidth of 350 kHz and can detect events (strokes) with a location accuracy (LA) between 250 m - 500 m and a detection efficiency (DE) of 90% for cloud-to-ground (CG) lightning and 10%–30% for cloud–to–cloud (CC) lightning for the highest efficiency zone of the country [24]. Nevertheless, in a study developed by Pérez *et al*. [25], the detection efficiency was found to be between 60% to 70%. It is important to remark that this study informed some issues about the LLS network such as poor calibration, few sensors, low coverage and the effect of the mountains in countries like Colombia, so the performance of the network is affected by such issues, a problem that needs to be analysed in future studies, specially a properly network detection efficiency and location accuracy. RMCAB data come from a network composed by 13 fixed stations and one mobile station. This network registers the levels of PM_{10}, $PM_{2.5}$, SO_2, NO_2, CO y O_3. Also some meteorological variables are measured, PM_{10} values are available online at http://201.245.192.252:81/ for 11 stations. RMCAB data were used to elaborate maps of PM_{10} spatial distribution over Bogotá City. It is important to remark that data from mobile station were not used for this study.

Figure 1 shows the geographic localization of Bogotá and its relative position with the sensors of the LLS network. As it can be observed, Bogotá is located in a place where the LA and DE is the highest, so there is a high confidence on the data analysis especially the number of lightning strokes detected in the period under analysis.

Figure 2 shows the geographic location for the 11 stations of the network. As it can be seen, a good coverage for Bogotá City is reached with such stations.

The methodology used in this study is composed by three items:

1. A rural area adjacent to the urban one is selected. It is necessary to satisfy that both areas have similar altitude and meteorological conditions. Figure 1 shows Bogotá and its surrounding altitudes.
2. It is necessary to divide both areas into small subregions (resolution). For this study, a 3km x 3km area was used. This resolution is defined based on previous studies carried out for the Colombian territory and its LLS [26, 27]. After the resolution is defined, the number of strokes in each subregion is counted, and
3. The number of strokes belonging to the urban area is averaged and the same procedure iscarried out for the rural area. Then, a comparison between both zones is developed using Eq. (1) [3]

ID	Station
1	Usaquén
2	Carvajal - Sevillana
3	Tunal
4	Parque Simón Bolívar
5	Las Ferias
6	Guaymaral
7	Kennedy
8	Suba
9	Puente Aranda
10	Sagrado Corazón
11	San Cristobal

Figure 2 Stations of Air Quality Network of Bogotá - RMCAB

The second set of data used is the annual average of particulate matter PM_{10}, registered by RMCAB.

PM_{10} distribution maps were used to observe if there is any spatial relationship between pollution and lightning information. Then a correlation analysis was carried out between annual average of PM_{10} and the number of strokes, giving special focus to the relation in places with high and low PM_{10} values, respectively.

3. Results

Figure 3 shows a spatial distribution of lightning activity for urban and rural zone during the year 2012. Within the red box, the rural zone used to compare lightning activity can be observed. The number of strokes for the urban zone was 95 while the number of strokes for the rural zone was 40 for the same year. Comparing both data, a percentage of change of 174.5% was observed for this year.

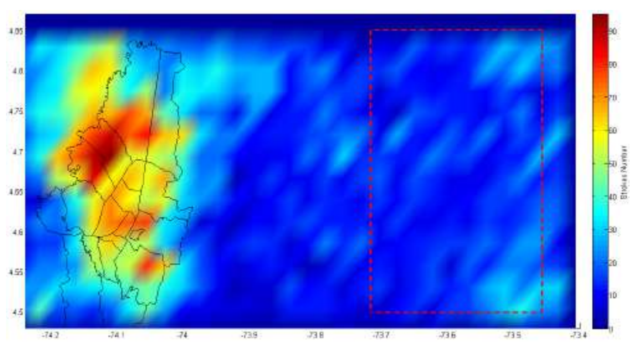


Figure 3 Map of lightning distribution over Bogotá and rural zone for 2012. The rural zone is within the red box

$$Percent\ Change = \frac{Mean\ strokes\ urban\ area - Mean\ strokes\ rural\ area}{Mean\ strokes\ rural\ area} \times 100 \quad (1)$$

Table 1 shows the percentage of change year to year and in Annex Section a map for every year can be analyzed. As it can be observed, the number of strokes has a variation between 33-340% for the period under analysis. This increase is consistent with other studies carried out for cities like Houston, São Paulo and Seoul [6, 8, 11, 28]. The mean value increase found for the period under analysis in Bogotá city: 146.8% is higher than the observed in the cited cities where increases of 45%, 100% y 42% respectively, were observed. Here it can be concluded that an influence of some phenomena of the city such as pollution, urban heat island, and the meteorological conditions of the city can exist.

Table 1 Percentage of change for the lightning activity between urban and adjacent rural areas of Bogotá

Year	(%)Change
2007	340.5
2008	107
2009	87.8
2010	33.0
2011	138.1
2012	174.5
Mean	146.8

As it was explained before, RMCAB data was used to create maps of spatial distribution of PM_{10} for Bogotá city. Figure 4 shows PM_{10} distribution for the year 2012. It can be observed that zones with higher levels of PM_{10} are *Kennedy* and *Carvajal*. Observing Figures 3 and 4, it can be determined that there are some likeness in the spatial distribution of strokes and PM_{10}, specially in the eastern zone of the city. It can be observed that for zones with values of PM_{10} between 42-57 *μgm–3* the number of stroke values are between *50-95 strokes*.

Figure 5 shows the relationship between the number of strokes and the value of PM_{10} for two zones with high values of PM_{10}. The number of strokes over each zone was sorted as a function of the particulate matter PM_{10}. As it can be seen, in both figures the tendency line is positive; however, both of them have a low correlation coefficient value of R^2 = 0.221 and R^2 = 0.202, for *Kennedy* and *Las Ferias*, respectively.

Figure 6 shows the relationship between the number of strokes and the values of PM_{10} for two zones with low levels of pollution. As it can be seen, there is no tendency defined. In a study carried out by Farias [6] for São Paulo

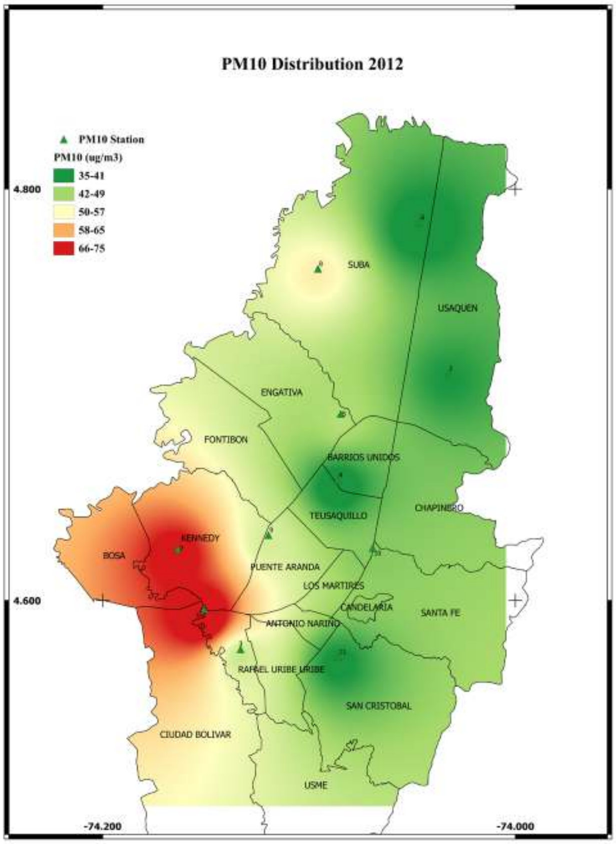
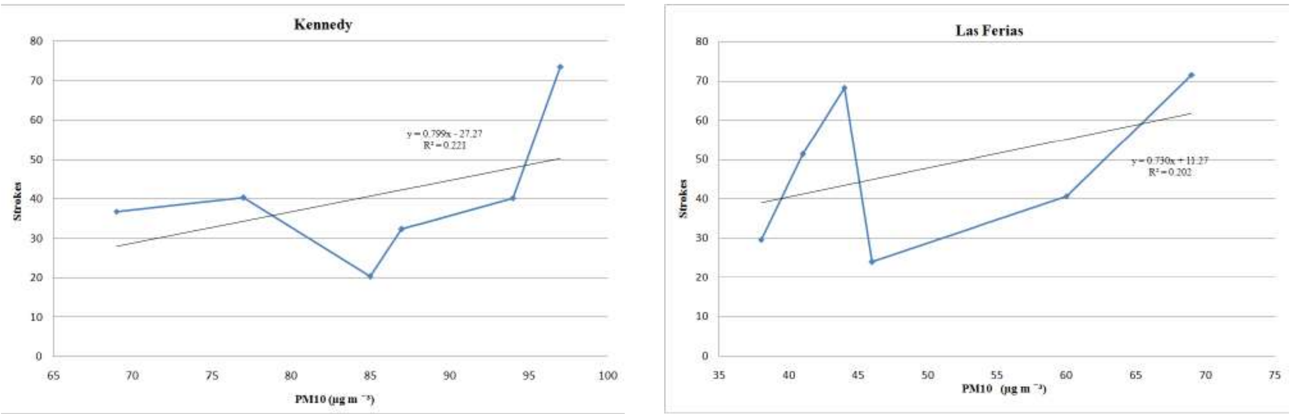
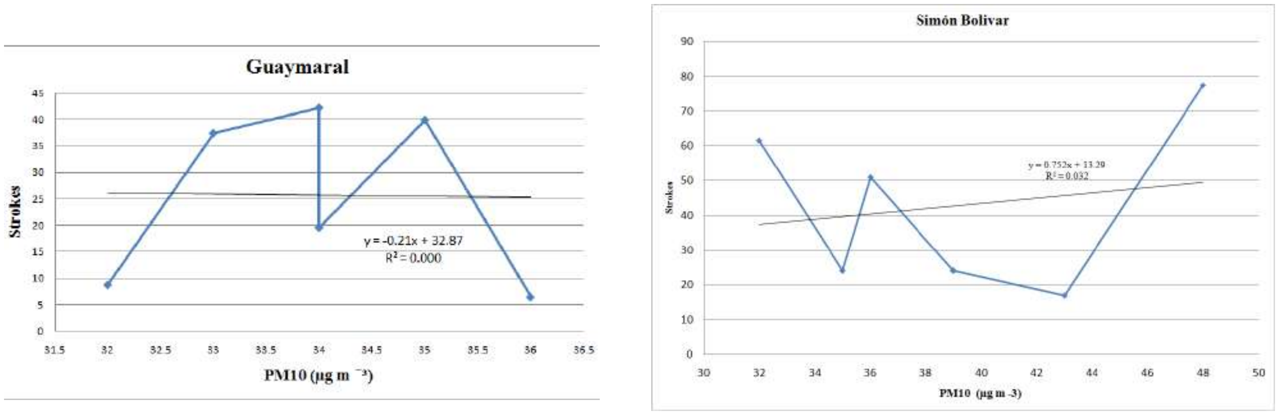


Figure 4 PM_{10} spacial distribution on Bogotá for the year 2012



(a) Kennedy (b) Las Ferias

Figure 5 Relationship between number of strokes and PM_{10} values for two zones with high pollution levels in Bogotá: (a) *Kennedy* and (b) *Las Ferias*



(a) Guaymaral (b) Simón Bolivar

Figure 6 Relationship between number of strokes and PM10 values for (a) *Guaymaral* and (b) *Simon Bolivar*. Zones with high pollution

city, it was observed that particulate matter can increase lightning activity if pollution levels are between 0-60 *µg m*$^{-3}$. Additionally, if the values are between 30-60 *µgm*$^{-3}$ the increase is faster, but if the values are between 60-90 *µgm*$^{-3}$ the lightning activity is saturated. For station Las Ferias Figure 5(b), it can be observed that pollution levels are between 38-69 *µgm*$^{-3}$ and the lightning activity increases. For Station *Kennedy* PM_{10} values are between 69-97 *µgm*$^{-3}$ and there is also a lightning increase tendency. The same phenomenon happens in Station *Simon Bolivar* that shows values between 32-48 *µgm*$^{-3}$; however, its correlation coefficient is not satisfactory $R^2 = 0.032$. In Station *Guaymaral* the pollution variation values are the lowest 32-36 *µgm*$^{-3}$ and there is not defined tendency.

As described by the above, it can be concluded that there is no specific correlation between number of strokes with PM_{10} value, nevertheless, a tendency in most of the figures can be observed demanding more and detailed studies.

4. Conclusions

Lightning is a phenomenon of high importance and relation with climate change. Its effects increase the risk to affect human beings, systems and equipments mainly in large and populated cities.

Anthropogenic effects over the climate in general, and over lightning phenomenon in particular deserve to be studied.

The lightning activity variation obtained when comparing urban and rural zones of Bogotá was found to be between 33-340% with a mean value of 146%.

It is important to remark that even in Colombia there are some regions reported with one of the highest lightning activity in world (Hot Spots) [21-23] with Flash Rate Density above 100, Bogotá is a place with a very low activity in comparison with the ones reported before, with values about 1 flash/km^2/year. The reason of this low value is due to geographic and orographic conditions of a city located in Andes Cordillera at 2,650 m.a.s.l where meteorological conditions do not allow this place to have a high lighting activity like in other places. Nevertheless, it is a very good region to develop a study of the anthropogenic influence in lightning activity for the reasons described in this work.

An analysis of the influence of anthropogenic factors, especially pollution, on lightning activity was carried out. The results showed that zones with high levels of particulate matter PM_{10} have also high levels of lightning activity (CG strokes).

PM_{10} and lightning activity are not very well correlated in three out of four of the zones analyzed in Bogotá city, but there is a tendency in those analysis that demands some additional and detailed studies in the future to assure if there exist or not a correlation between those factors. These results are consistent with other studies carried out in other cities like Houston, São Paulo, Belo Horizonte and Seul.

Despite the results obtained in this study, it is necessary to keep studying and developing deeper and bigger analyses that allow correlating topography and other meteorological variables such as winds, temperature, precipitation and some others.

Additionally, there are some studies [5] which found that urban heat island can affect even more the thundercloud formation than pollution, due to the variation of the temperature gradient that affects the local circulation; then, this kind of variables demand to go further in the analysis for future studies, starting from the premise that Bogotá has an Urban Heat Island of 3 °C reported by [2, 20] with data analysis for more than 40 years.

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6. Annex

This annex shows the spatial distribution of strokes and PM10 over the Bogotá city in the period of years 2007 – –2012 (Figure 7 to 12).

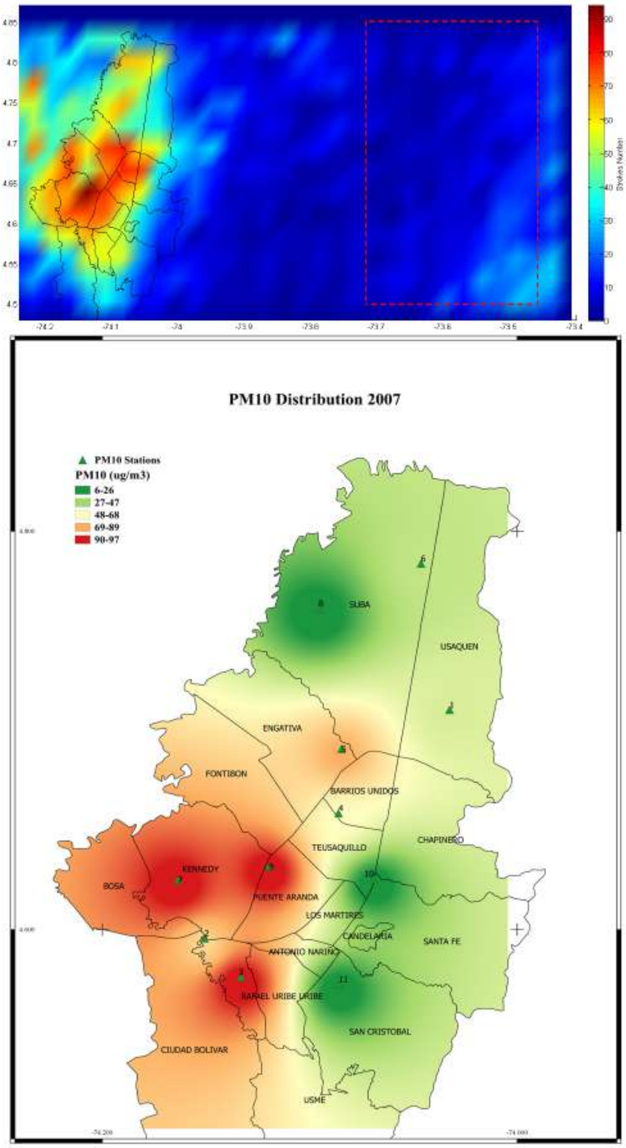

Figure 7 Strokes distribution 2007 and PM_{10} distribution 2007 on Bogota

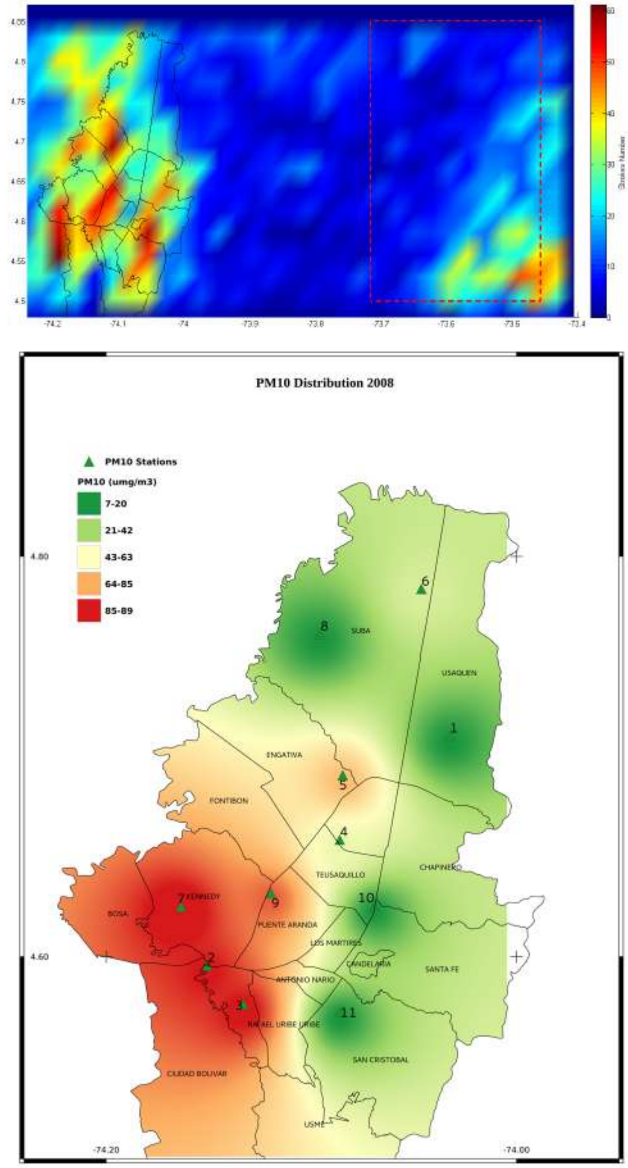

Figure 8 Strokes distribution 2008 and PM_{10} distribution 2008 on Bogota

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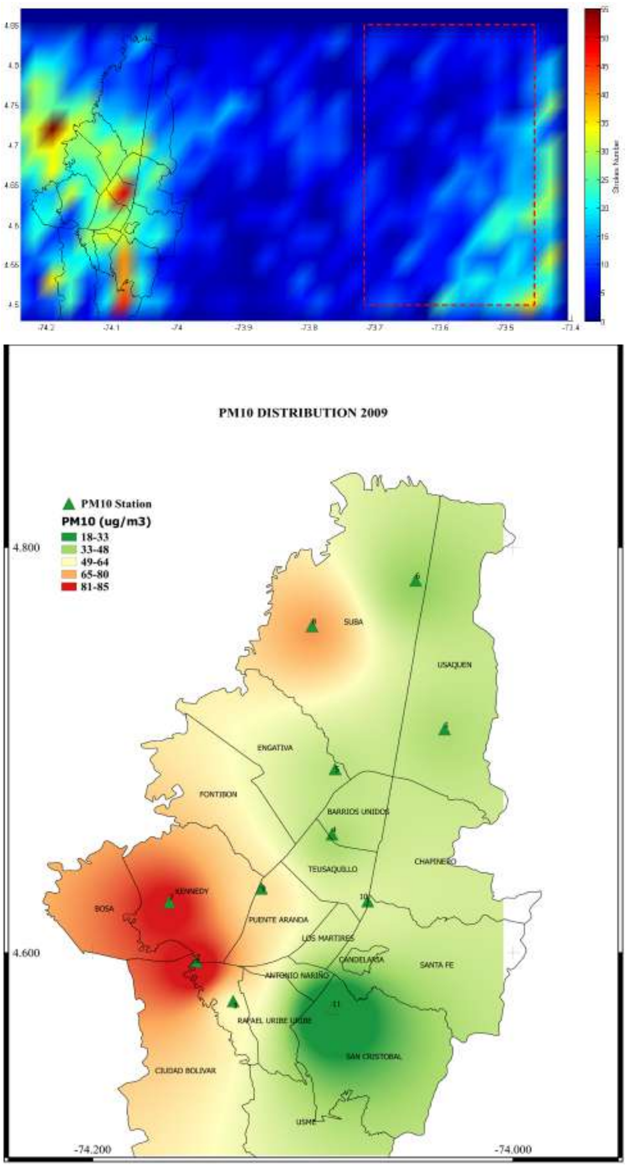

Figure 9 Strokes distribution 2009 and PM_{10} distribution 2009 on Bogotá

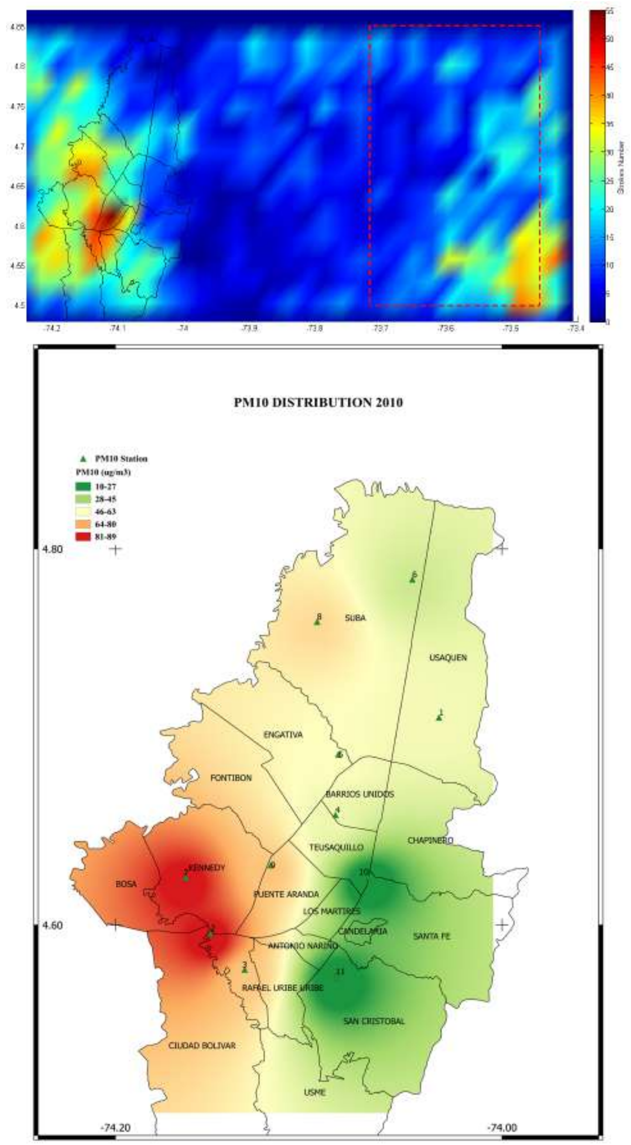

Figure 10 Strokes distribution 2010 and PM_{10} distribution 2010 on Bogotá

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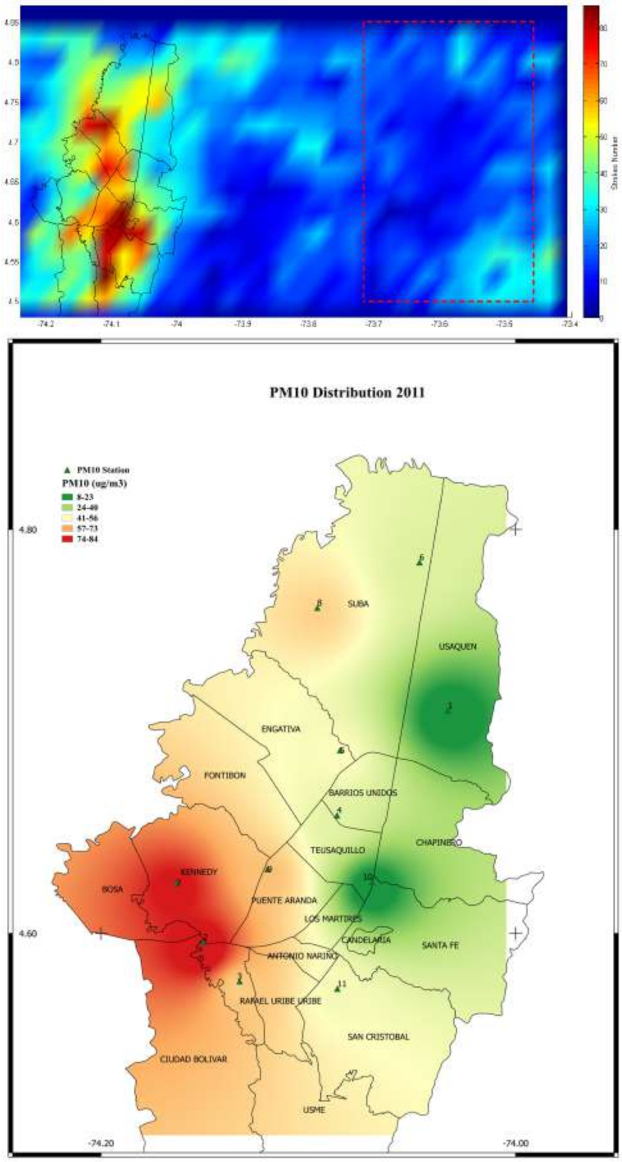

Figure 11 Strokes distribution 2011 and PM_{10} distribution 2011 on Bogota

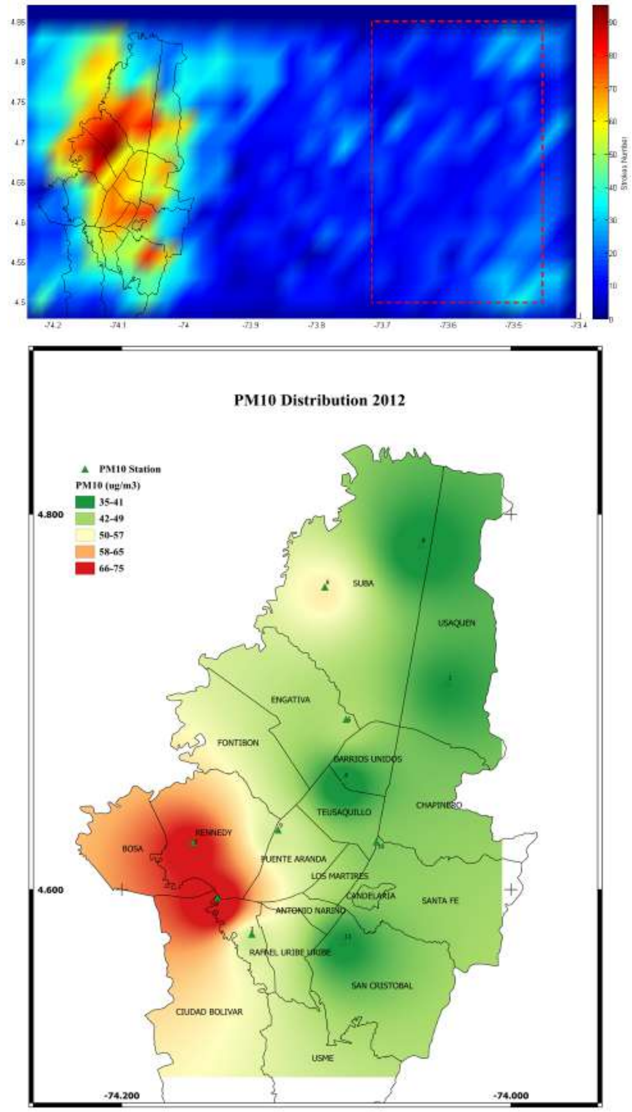

Figure 12 Strokes distribution 2012 and PM_{10} distribution 2012 on Bogota

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