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Aerosol effects on the enhancement of cloud-to-ground lightning over major urban areas of South Korea

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ABSTRACT

A long term (1989–1999) investigation has been made using the cloud-to-ground (CG) lightning flash data collected to study the aerosol effect on lightning activity over five major urban areas of South Korea. The cloud-to-ground (CG) lightning data were collected from the Korean Meteorological Administration (KMA) of South Korea. The results reveal that an enhancement of around 40–64% in the negative flash density and 26–49% in the positive flash density is observed over the urban areas compared to their surroundings. On the other hand a percentage decrease of around 7–19% in positive flashes occurs over the urban area. The results are in good agreement with those available in the literature. The enhancement of lightning is examined in relation to the PM10 (particulate matter with aerodynamic diameter smaller than 10 μm) and SO_2 concentrations. The PM10 and SO_2 concentrations exhibit a positive linear correlation with the number of cloud-to-ground flashes, while a negative correlation is observed between those concentrations and the percentage of positive flashes. Positive correlations of 0.795 and 0.801 are found for the PM10 and SO_2 concentrations, respectively, when compared separately with the number of CG flashes, establishing the effect of aerosols on urban CG lightning enhancement. However, negative correlations of −0.577 and −0.548 are obtained for the PM10 and SO_2 concentrations, respectively, when compared separately with the percentage of positive flashes.

1. Introduction

Despite considerable research about the influence of urban areas on local weather (Huff and Changnon, 1973; Braham et al., 1981; Changnon et al., 1981; Landsberg, 1981; Balling and Idso, 1989; Orville et al., 2001; Steiger et al., 2002; Soriano and Pablo, 2002), our present understanding is incomplete. Shepherd (2005) showed, critically reviewing the available investigations, the complexity of obtaining a better understanding of the influence of the urban environment on the climate and the interaction of the Earth's atmosphere–ocean–land–biosphere components as a coupled system. Several issues or questions were raised in the United States' Climate Change Science Program plan (Climate Change Science Program and Subcommittee on Global Change Research, 2003) about the role of urban environments on the Earth system and local weather. Among the various issues the effects of cities and polluted areas on lightning has been of recent interest. The urban effect on enhancing cloud-to-ground (CG) lightning activity was first documented by Westcott (1995). After Westcott many studies relating to the effect of an urban area on the local weather activities have been conducted in different geographical locations of the globe (e.g., Changnon et al., 1981; Landsberg, 1981; Balling and Idso, 1989; Orville et al., 2001; Steiger et al., 2002; Soriano and Pablo, 2002). Most of these studies have ascribed the effect to the urban heat island circulation along with a possible role of air pollution. By conducting a long-term study Steiger et al. (2002) have shown that not only the CG flash density is affected by the urban area of Houston but also that the percentage of positive flashes is affected, decreasing with the increase of total number of flashes. A −12% decrease in the percentage of positive flashes was found in their study, but no significant effect on the peak current of negative and

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positive CG flashes was observed. Enhancement of CG lightning over small urban areas in central Spain and over large Brazilian urban areas has been documented by Soriano and Pablo (2002) and Naccarato et al. (2003), respectively. Local topographical effects, enhanced convergence associated with the urban heat island and microphysical effects due to increased levels of cloud condensation nuclei (CCN) in the urban environment have been regarded as the most significant cause of enhanced lightning over urban areas. However, it is yet to be computed what the relative contribution of these effects to lightning enhancement is.

Common components of urban air pollution are particulate matters, or aerosols. Aerosols play the crucial role of cloud condensation nuclei for the formation of precipitation. Therefore urban effects on lightning are expected because of the well established physical relationship between lightning activity and precipitation (Petersen and Rutledge, 1998; Soriano et al., 2001; Kar and Ha, 2003) and for the similarity in formation mechanism between lightning and precipitation. Pollution over the cities can elevate the cloud condensation nuclei (CCN) concentration, which in turn might produce changes in the microphysical processes taking place inside the clouds. Owing to such changes in cloud microphysical processes, a change in the charge separation processes in thunderclouds is expected to occur because of its dependence on the concentration, phase and size of cloud particles. Increased pollution in the boundary layer is expected to be operative in suppressing the mean droplet size, and more cloud water would therefore be operative in separating the electric charge, leading to a creation of more CG lightning flashes (Orville et al., 2001). Westcott (1995) was the first who suggested the possible influence of high PM10 and SO_2 concentrations on the enhancement of urban CG lightning activity. Thereafter Orville et al. (2001) reported an association of urban heat island and anthropogenic pollution in the enhancement of the flash density over and downwind of the urban area after conducting a long term analysis over the city of Houston.

Many studies on thunderstorms and lightning are found in the literature over tropical areas and in the United States; compared to those studies the number of studies relating to mid latitude areas, specifically to the Korean peninsula, is limited. No attempt has yet been made to investigate the urban effect on lightning activity over the South Korean peninsula, except for a few studies on lightning and precipitation (Kar and Ha, 2003; Lim and Lee, 2002). In this paper, a long term analysis of lightning data is conducted over five metropolitan cities of South Korea. The urban areas associated with these five cites are shown in Table 1. Positive and negative flash density and the percentage of positive flashes have been calculated. The results are presented and compared to those available in the literature. Special emphasis is given to the investigations of the possible influence of PM10 and SO_2 on lightning activity, and the results are compared. To the best of our knowledge, this is the first long-term study of the aerosol effect on lightning activity over the South Korean peninsula.

Table 1
Name of the five metropolitan cities under study and the urban areas associated with them

Name of the metropolitan cities	Latitude	Longitude	Urban area in km^2
Busan	35°06′	129°02′	198
Incheon	37°29′	126°38′	228
Daegu	35°52′	128°36′	210
Taejon	36°19′	127°42′	209
Gwangju	35°10′	126°55′	155

2. Data and methodology

The Korean Meteorological Administration (KMA) has a very good lightning detection network which consists of an advanced Position Analyzer, Model 280 (APA), Advanced Display System (ADS), Network Display System (NDS), Integrated Storm Information System (ISIS) and Advanced Lightning Direction Finder (ALDF, model 141), made by Lightning Location and Protection, Inc., which at present is known as Vaisala of Tucson, Arizona. The network can detect only CG flashes. For our present analysis we have collected cloud-to-ground lightning data from KMA for the period 1989–1999. The lightning sensors used by this network have been elucidated in depth by various authors (Orville et al., 1983; Lopez and Holle, 1986). Each magnetic direction finder of the network detects the cloud-to-Ground (CG) lightning strikes and determines a direction toward a detected electromagnetic lightning discharge. After being detected, each lightning event is transmitted to the position analyzer for its polarity, amplitude, latitude, longitude, date and time of occurrence determination. A direction finder can detect automatically approximately 80%–90% of all CG lightning, which occurs within a nominal detectable distance of 400 km with less than 4-km accuracy. However, the assumption of 80% uniform flash detection efficiency may not be realistic, particularly near the edges of the network. We have not made any attempt to correct the detection efficiency of the lightning network. A complete description of the network and its detection efficiency has been summarized by Cummins et al. (1998a,b) of Vaisala, Inc., from its past to its present form. It has been found in many earlier studies that this type of lightning network is subjected to contamination by intra-cloud lightning flashes. Keeping this information in mind, only CG flashes with a first stroke peak current larger than 15 kA have been considered in our study. It is to be noted that although, especially for positive flashes, the contamination by intra-cloud flashes may extend above this threshold, the above findings have no influence on the results presented in this paper.

A spatial scale of approximately 0.08° latitude × 0.08° longitude has been considered for the present study. The number of CG flashes within the specified block surrounding each city has been counted. The area associated with each grid box is ~8.8 km × 6.6 km ~ 58 km^2. Since the urban area of each city is different, the blocks associated with each urban area consists of a different number of grids. The number of lightning flashes in each block is counted for a ten year period and then averaged. Ignoring the polarity of the lightning flash, we have calculated the total number of CG flashes over each metropolitan city. In contrast, flash densities of both polarities and the percentage of positive flashes are calculated by giving special attention to the polarity of lightning flashes.

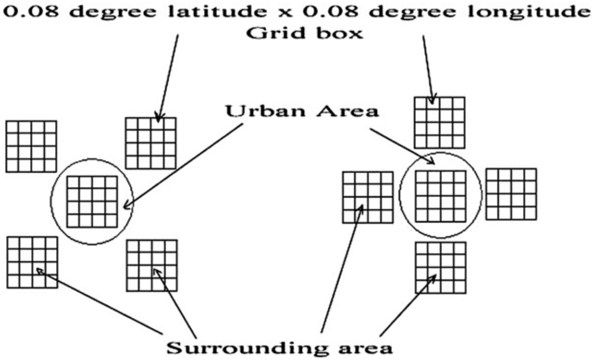

Fig. 1. Graphical presentation of urban and surrounding area methodology.

The calculation of the negative flash density, positive flash density and percentage of positive flashes, have been made in a way similar to that used to make the total lightning counts. For computing the percentage increase of lightning flash density over a particular region, we have taken the difference of the average flash density between that particular region and its neighbouring region over an equal area, divided it by the average flash density of the neighbouring region and finally multiplied the number by one hundred. The number of grid boxes in the surrounding areas of each city, for computing the number of lightning flashes, is equal to the number of grid boxes within that city area in which lightning flashes were counted for urban area. Fig. 1 illustrates the urban and surrounding area methodology. The location of the five metropolitan cities under study and the location of the sensors used by the lightning detection network are marked in Fig. 2. An automatic detection of nearly 90% of all cloud-to-ground lightning occurring within a nominal detectable distance with less than 1 km accuracy was done by the sensors, as shown in Fig. 2.

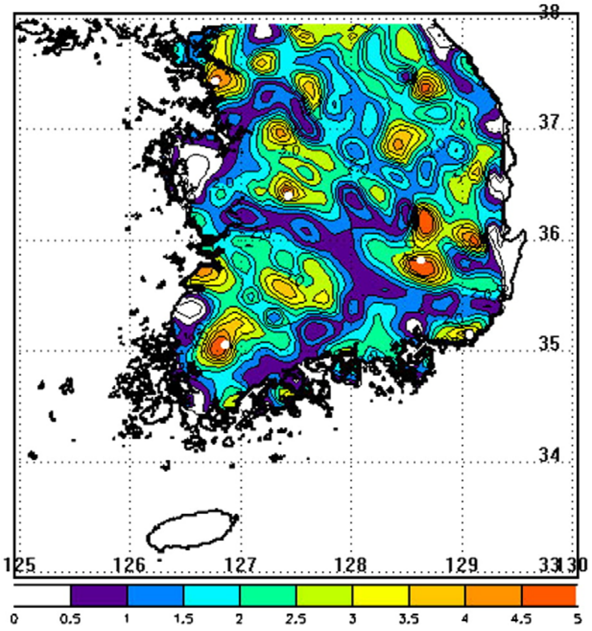

Fig. 3. Spatial distribution of mean annual negative flash density over South Korea. Flash densities are in (fl km^{-2} yr^{-1}) and for the years 1989–1999. White dots indicate the location of the stations under study.

3. Results and discussion

The spatial distribution of the mean annual negative and positive flash density over South Korea is presented in Figs. 3 and 4, respectively. Significant enhancement of the negative

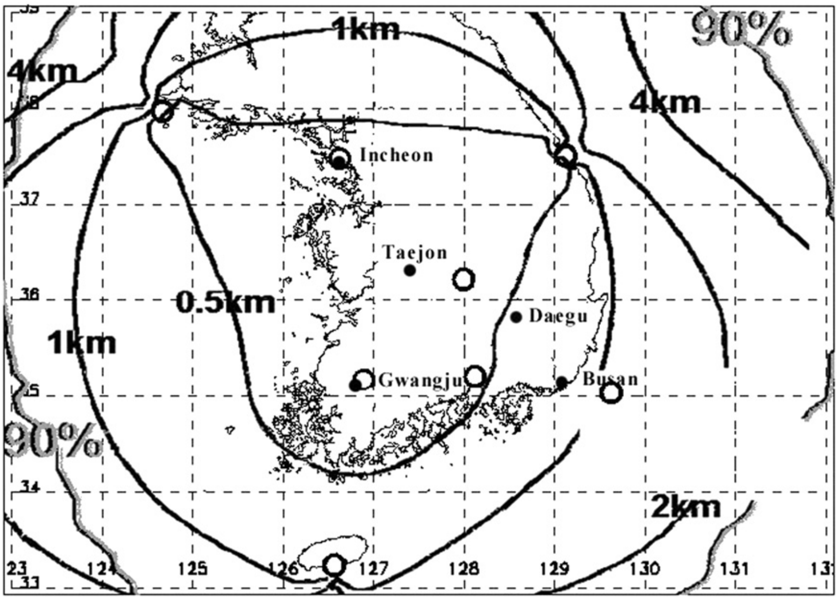

Fig. 2. Location of the sensors of the lightning detection network and the location of five metropolitan cities under study. Thick black and gray lines are system accuracy and detection efficiency, respectively. Small circles (o) indicate the location of lightning stations.

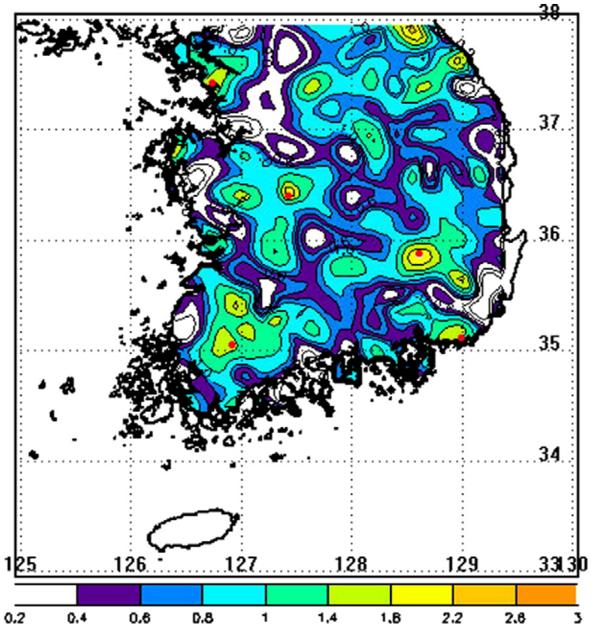

Fig. 4. Same as in Fig. 3 but for positive flash density. Red dots indicate the location of the stations under study. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

and positive flash density is noticed over all the five metropolitan cities under study. The percentage increase of the mean annual negative and positive flash density, over the five metropolitan cities of South Korea compared to the surrounding areas of each city has been calculated. It was found that the percentage enhancement varies from one city to another. The percentage increase of both the mean annual negative and positive flash density is maximum over Daegu, while the minimum of the said two parameters is observed over Taejon and Incheon. In the case of negative flash density, an enhancement of 40–64% is observed, while for the positive flash density, the enhancement varies from 26–49% compared to the nearby surrounding areas. The values of percentage variation for negative and positive flash densities correspond well with the results reported by Westcott (1995) and Steiger et al. (2002). However, Pinto et al. (2004) reported a bit higher value compared to our results. It is interesting to note that, besides the lightning enhancement over the five metropolitan cities under study in Fig. 3, there are some other locations where similar lightning enhancements were also observed. The lightning density spots along the north east coast might have originated due to the local topographic features, as these points are on the Tae-baek Mountain spreading parallel to the entire east coast from north to south. While the other lightning density spots to the northeast of Gwangju are situated over the northeast–southwest elongated Sobaek Mountain. The lightning spots north of Daegu and Taejon occurred over other small urban areas, but have not been considered in the present study as the aerosol data for those semi urban areas were unavailable.

The percentage variation of positive flashes over each city compared to its surrounding areas is depicted in Fig. 5. It is interesting to note that, in the case of percentage positive flashes, a significant decrease occurs over each city compared to its surrounding areas, and the percentage positive flash varies by 7–19%, as is evident from Fig. 5. The largest decrease was observed over Gwangju while the lowest decrease was noticed over Daegu. The value of percentage decrease found in the present analysis agrees fairly well with the results reported by Steiger et al. (2002). Steiger et al. (2002) noticed a decrease of −12% over Houston compared with surrounding areas. However, our results differ from the findings obtained by Lyons et al. (1998) and Murray et al. (2000), who presented an opposite effect for thunderstorms in the central USA. A significant increase in the percentage of positive flashes in thunderstorms which was contaminated by forest fire aerosol plumes is indicated in their study. Microphysical processes of charge separation in a thundercloud could provide a possible explanation for the decrease of percentage of positive flashes, as has been found in our study. Jayaratne et al.

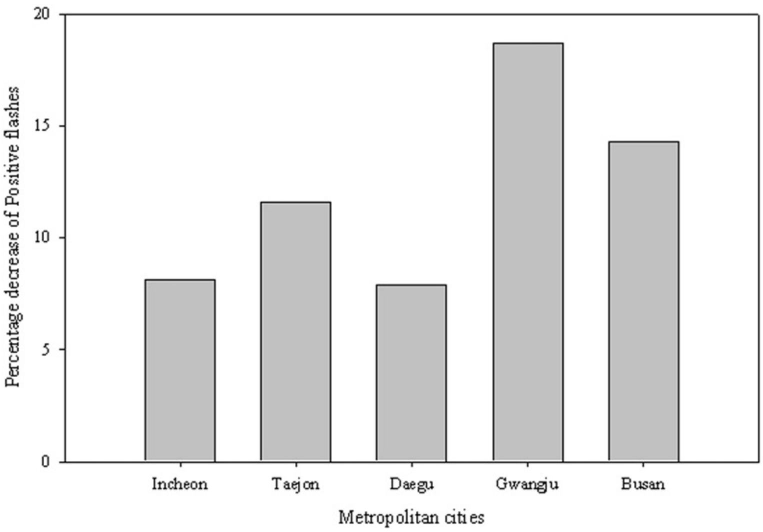

Fig. 5. Variation of percent positive flashes over five metropolitan cities of South Korea for the years 1989–1999.

(1983) suggested that the sign and magnitude of charge transfer to the graupel target is largely dependent on the impurities in the cloud water during ice crystal interaction. Anthropogenic particulate impurities in cloud water can affect the charge separation in the urban thundercloud appreciably by increasing the negative lightning activity (Steiger et al., 2002). High concentrations of contaminants in supercooled cloud droplets led to negative charging of graupel at warmer cloud temperatures. The occurrence of such a negative graupel charging due to increased impurities in the cloud water at higher temperatures could extend itself towards the cloud base, covering the positive charge center below (Pruppacher and Klett, 1997, Fig. 18-2). This newly formed stretched region of negative charge of the thunderstorm tripolar charge distribution model (MacGorman and Rust, 1998) may produce more negative CG flashes, decreasing the relative frequency of positive flashes. For a smaller-droplet spectrum, Avila et al. (1999) have found that over most of the temperature range (−10 °C to −25 °C) the target graupel is charged positively. On the other hand negative charging of the target graupel is observed for a larger droplet spectrum at temperatures below −18 °C during ice–ice collisions in the presence of super cooled water. This speculation indicates an existence of a deeper positive charge center in the lower region of a thunderstorm containing a smaller droplet spectrum. This deeper positive charge center intensifies further the possibility of a higher percentage of positive values over an area favorable for the formation of such types of droplet spectrum or over a polluted air mass. This concept can reasonably elucidate the enhancement of the percentage of positive CG flashes in thunderstorms which are generally produced in smoke-contaminated air masses (like forest fires), but is unable to explain the effect over urban areas. But recent research of Andreae et al. (2004), conducted over extreme pyro-clouds, showed that aerosol particles in a smoky region, despite their vastly different concentrations, different source mechanisms and compositions, are basically similar to clean region aerosol particles in their ability to nucleate cloud droplets. They have shown that the material, originated from the “conversion” of biological material to aerosol, is similar in its gross chemical composition and solubility, despite its differences in actual organic compounds. Hence, similar CCN properties and CCN efficiency between the clean region and the cloud-processed smoke aerosols are expected to be observed.

Anthropogenic aerosols are the other main source of metropolitan air. Many studies have been conducted so far to probe whether there is any influence of such pollution on the enhancement of lightning. Mather (1991) reported that the clouds downwind of particulate sources produce more rain than other storms. Results of these studies indicate that pollution can enhance convection over urban areas. Conflicting remarks are also found in the literature. Shepherd (2005) made an extensive review considering both observational and modeling studies of urban induced rainfall and showed that an uncertainty in the role of urban aerosols on precipitation is clearly evident. The annual averages of PM10 and SO_2 concentrations for each city have been considered in relation to the percent change of CG flashes to ascertain the possible effect of urban particulate matter on CG lightning activity. We have assumed the concentrations of PM10 and SO_2 to be gross indicators of the CCN concentrations. We have chosen PM10 due to convenience of the data as a proxy for polluted air. It is worth mentioning in this context that the examination of PM2.5 along with PM10 would have been better, since the fine particles are more likely to stabilize clouds. But PM2.5 is generally not measured routinely for all the stations under study, and so high concentration episodes occurring between measurements would not be reflected in the average, possibly leading to some exposure misclassification. Therefore we have restricted our analysis to only within PM10. Because of the availability of PM10 and SO_2 data only for a period of 1995 to 1999, we are compelled to restrict our lightning data analysis for five years to maintain a consistency among the data sets. Fig. 6(A) shows the scatter plot of CG lightning flashes with PM10 concentrations, while Fig. 6(B) exhibits the scatter plot of the percentage of positive flashes with PM10 concentrations over the five cities under consideration. Standard deviations have been calculated from the data set of annual averages of both the parameters for the period of

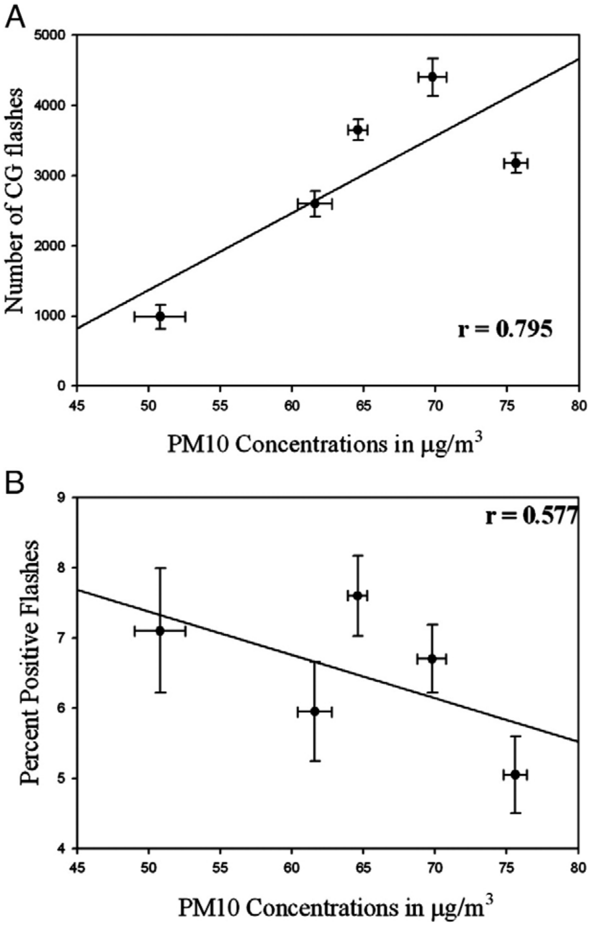

Fig. 6. (A). Scatter plot and best-fit line of the number of CG flashes and annual averages of PM10 concentrations for the years 1995–1999. Horizontal and vertical bars represent the standard deviations of *x*-values and *y*-values respectively. (B). Scatter plot and best-fit line of percent positive flashes and annual averages of PM10 concentrations for the years 1995–1999. Horizontal and vertical bars represent the standard deviations of *x*-values and *y*-values respectively.

1995 to 1999. Fig. 6(A) exhibits a positive correlation between the two plotted parameters. On the other hand, Fig. 6(B) exhibits a negative correlation between the two plotted parameters. In Fig. 7(A) and (B) we have shown the scatter plot of SO_2 concentrations with CG lightning flashes and the percentage of positive flashes, respectively. Standard deviations in this figure have also been calculated from the data set of annual averages of both the parameters for a period of 1995 to 1999. As before, in the case of SO_2 also we get a positive correlation between the SO_2 concentrations and the number of lightning flashes and a negative correlation between the SO_2 concentrations and the percentage of positive flashes. A significance test has been made taking the standard deviations into account to test the statistical significance of the above differences between the two correlation coefficients in Figs. 6 and 7. It has been found that the computed z value is greater than the cutoff value at the significance level 0.05 for Figs. 6(A) and 7(A), but it is much smaller than the cutoff value in the case of Figs. 6(B) and 7(B). Therefore, the correlations in Figs. 6(A) and 7(A) are statistically significant, while the correlations in Figs. 6(B) and 7(B) are statistically insignificant at the 0.05 level. These results indicate a possible influence of aerosol concentrations on the number of CG lightning flashes, but not on the percentage of positive flashes. It is important to note that, although the negative linear correlations between the percentage of positive flashes and aerosol concentrations, as shown in Figs. 6(B) and 7(B), apparently indicates a positive incremental tendency of the percentage of positive CG flashes with the aerosol concentrations, but the correlations are not significant when the standard deviations are taken into account. Therefore our results do not corroborate the other results, which indicate an incremental tendency of the percentage of positive CG flashes with the increase of aerosol concentration (Lyons et al., 1998; Murray et al., 2000). However, Orville et al. (2001) has suggested that the production of CG lightning is enhanced by the increase cloud water in the mixed phase region and is paralleled by an increase in the electrical charge separation. Since the sulphate particles are usually more active in the formation of cloud droplets compared to PM10 (Seinfeld, 1975), a slight higher contribution from SO_2 concentration is expected to enhance the CG lightning compared with the PM10 concentration. Our results partially correspond to the report of Soriano and Pablo (2002), but corroborate well the results of Westcott (1995). Westcott (1995) has found that large annual values of SO_2 and PM10 correspond generally to the large values of urban and downwind CG flashes. On the other hand Soriano and Pablo (2002) found PM10 to be a non influential parameter in the enhancement of urban lightning distribution.

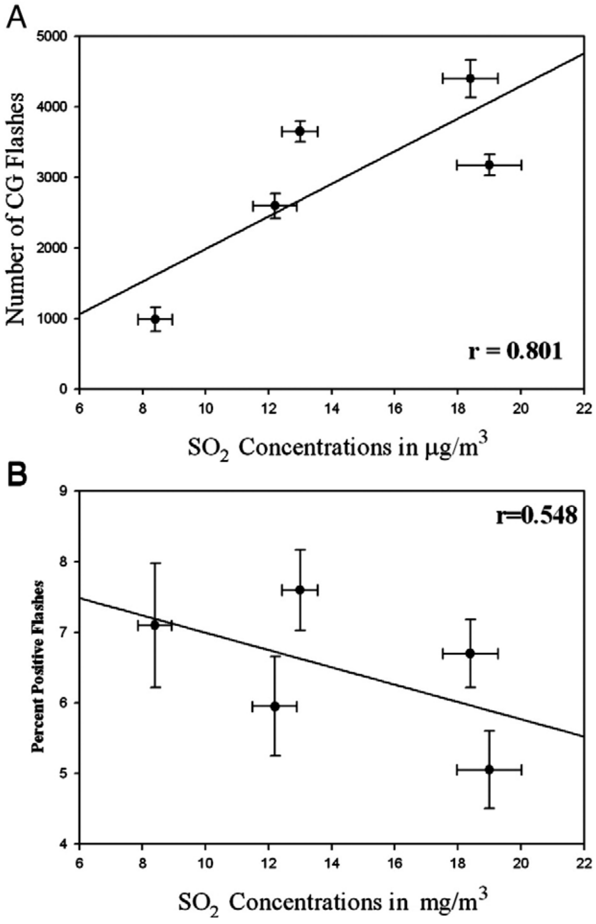

Fig. 7. (A). Same as Fig. 6(A) but for SO_2 concentrations. Horizontal and vertical bars represent the standard deviations of x-values and y-values respectively. (B). Same as Fig. 6(B) but for SO_2 concentrations. Horizontal and vertical bars represent the standard deviations of x-values and y-values respectively.

Several hypotheses for lightning flash modification were presented in the literature but a possible explanation of the aerosol effect on lightning production, as observed in our present study, can be found in Rosenfeld–Lensky hypothesis (Rosenfeld and Lensky, 1998; Williams et al., 1999). Rosenfeld and Lensky (1998) have shown, analyzing the Advanced Very High Resolution Radiometer (AVHRR) data, that a very narrow or no coalescence zone, a deep mixed-phase zone and glaciation occur at higher levels for the clouds forming over polluted regions compared to relatively less polluted rural clouds. In our present analysis we have considered the annual number of lightning flashes and the annual average concentrations of PM10 and SO_2. The higher CCN concentration over each metropolitan city results in the reduction of the mean cloud droplet size, which in turn decreases the process of coalescence and the droplet collision efficiency (Rogers and Yau, 1989). Hence, it can be concluded that more supercooled water can exist at greater depths in clouds generated in a polluted atmosphere. Saunders (1993) has reported the dependence of the noninductive charge separation process on the amount of supercooled liquid water in the thundercloud. The abundance of supercooled water may generate large graupel, which in turn may produce enhanced storm electrification through collisions with ice particles. Enhancement of cloud buoyancy is also possible through the freezing process by the excess cloud water in the mixed phase zone. Steiger et al. (2002) also showed the Rosenfeld–Lensky theory to be a crucial factor in explaining the urban enhancement of CG flashes. It was mentioned by Steiger et al. (2002) that the cities are thermodynamically less propitious for thunderstorm formation. Copious numbers of CCN can greatly reduce the coalescence process in urban thunderclouds, owing to the increase of droplet number, and thereby suppress the mean size of droplets. This diminution in coalescence process could increase the charge separation in the thundercloud by enhancing the liquid water content in the mixed phase region, and in turn produce increased lightning activity (Steiger et al., 2002). Satellite measurements of the aerosol optical depth and cloud top pressure also indicated a correlation between the aerosol concentrations and the structural properties of clouds, suggesting a possible cloud invigoration by pollution (Koren et al., 2005). Rapid industrialization and urbanization in Asia have caused severe air pollution over many countries and a dramatic increase in aerosol concentrations over Asia has been found from long-term satellite measurements (Lelieveld et al., 2001; Massie et al., 2004). Enhanced deep convection and mixed-phase processes associated with such urban pollution have also been implicated in elevated electrification and enhanced lightning activities in thunderstorms (Orville et al., 2001; Zhang et al., 2004). Recent research conducted by Stallins and Rose (2008) showed that the spatial and temporal contingencies of aerosol content, moisture availability, and boundary-layer instability are the more geographically variable phenomena that constrain thunderstorm formation and lightning production. Hence, extensive study is required taking data from other geographical locations and for more years to resolve this diversity in findings.

4. Conclusions

Using the lightning data from KMA for a period of 1989–1999, an extensive long-term climatological study over five metropolitan cities of South Korea has been conducted. Results indicate an enhancement of 40–64% and 26–49% in the negative and positive flash density, respectively, over the urban areas compared to their surroundings. On the other hand a percentage decrease of 7–19% in positive flashes occurs over the urban area of each city under study compared to their surrounding areas. Our results agree fairly well with the results obtained by Steiger et al. (2002). We have assumed the PM10 and SO_2 concentrations to be a gross indicator of CCN and they been analyzed in relation to the CG lightning activities. A positive linear correlation is found between the number of CG flashes and a higher concentration of both SO_2 and PM10, indicating a possible link between aerosol concentrations and enhancement of lightning flashes. These results corroborate partially the results of Soriano et al. (2002), who found a positive correlation between SO_2 concentrations and an enhancement of lightning flashes. On the other hand, an apparent negative linear correlation is obtained between those two aerosol concentrations and the percentage of positive flashes. But the correlations are statistically insignificant. Hence this observation differs from the results obtained by Lyons et al. (1998) and Murray et al. (2000), who presented an opposite effect for thunderstorms in the central USA. Positive correlations of 0.795 and 0.801 are found for the PM10 and SO_2 concentrations, respectively, when compared separately with the number of CG flashes. It is interesting to note that for SO_2 concentrations a slightly higher positive correlation, as expected and explained in an earlier section, is found compared to the PM10 concentrations. However negative correlations of −0.577 and −0.548 are obtained for the PM10 and SO_2 concentrations, respectively, when compared separately with the percentage of positive flashes. This higher positive correlation strongly supports that the aerosols play a key role in the enhancement of lightning activity, as also suggested by Steiger and Orville (2003) and Naccarato et al. (2003) from their experiment conducted over Houston, Texas and Brazilian urban areas, respectively. Williams et al. (1999) first proposed in their pollution hypothesis that under continental and dirty boundary layer conditions, the available liquid water in the storm updraft is shared amongst an innumerable number of small droplets, thereby suppressing the mean droplet size and thwarting the coalescence process. As a result of this, the cloud water reaches the mixed phase region to participate in creating excess cloud buoyancy, in precipitation formation, and in electric charge separation and increasing the lightning activity.

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