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Enhancement of cloud-to-ground lightning activity over Taipei, Taiwan in relation to urbanization

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ABSTRACT

Collecting the cloud-to-ground (CG) lightning flash data from Tai-Power Company of Taiwan, a long term study has been performed to investigate the enhancement of lightning activity in and around Taipei City, the largest metropolitan city of Taiwan, in relation to urbanization, for the period of 2005–2010. Results reveal that negative flash density is enhanced by approximately 64% while the positive flash density is enhanced by 48%, over and downwind of the city compared with other neighboring areas. On the other hand a decrease of nearly 24% in the percentage of positive flashes occurs over and downwind of Taipei compared to upwind values. We have also investigated the effect of urbanization on peak current of both polarities but no significant effect is noticed. Possible influence of urban particulate matter on the enhancement of CG lightning activity has been analyzed utilizing the annual averages of PM10 (particulate matter with aerodynamic diameter smaller than 10 μm) and SO_2 (sulfur dioxide) concentrations data. Interesting results are found, indicating the higher concentrations of PM10 and SO_2 contributes to the CG lightning enhancement. Both the concentrations exhibit a positive linear correlation with the percent change in CG flashes from the upwind to the urban area and from the upwind to the downwind area. However, the correlation coefficient for PM10 concentrations is comparatively much lower than SO_2 concentrations. Positive correlations of 0.55 and 0.68 are found for the PM10 and SO_2 concentrations, respectively, when compared separately with the percent change in CG flashes from the upwind to the downwind area, indicating the influence of aerosols on urban CG lightning enhancement. Hourly variation of lightning flashes show that the urban effects on CG lightning is prominent in the afternoon and early evening hours. The results obtained from the present analysis corroborate the results reported in the literature by other researchers.

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1. Introduction

The first indication of the effect of urban area on the enhancement of the cloud-to-ground (CG) lightning activity over and downwind of cities has come through the literature published by Westcott (1995). Thereafter several studies have been conducted to study the effect of an urban area on the initiation and enhancement of CG lightning (e.g. Orville et al., 2001; Steiger et al., 2002; Soriano and Pablo, 2002; Naccarato et al., 2003; Pinto et al., 2004; Farias et al., 2009; Lal and Pawar, 2011; Farias et al., 2014). In general, the urban heat island circulation and the possible role for air pollution have been indicated as the prime influencing factor behind such enhancement in most of these studies. Apparently the urban effect is a combination of an increased pollution concentration in the local air caused primarily by human activities and a thermodynamic effect due to differential heating of the city surface (Farias et al., 2009). Steiger et al. (2002) first conducted a 12-year climatological analysis over Houston, Texas on the percentage of positive flashes and peak current to investigate the urban effect on

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lightning characteristics in these categories. A decrease of (−12%) in the percentage of positive flashes and no significant effect on the peak current of negative and positive CG flashes are reported in their study. Because of the existence of a physical relationship between lightning activity and convective precipitation (Petersen and Rutledge, 1998; Soriano et al., 2001; Kar and Ha, 2003), urban effects on lightning are expected. The concentration of cloud condensation nuclei (CCN) over urban area can be uplifted by the pollution over the cities, which, in turn, may change the cloud microphysical processes. Such changes in cloud microphysical processes, again in turn, may change the charge separation processes in thunderclouds because of its close association with concentration, phase and the size of cloud particles. Orville et al. (2001) indicated that in the boundary layer, the increased pollution is expected to be effective in suppressing the mean droplet size, and more cloud water would therefore be operative in isolating the electric charge, leading to the production of enhanced CG lightning flashes. Recent study conducted by Farias et al. (2014) suggests that urban pollution tends to saturate the intensification of storms and lightning activity in a specific level. Andreae et al. (2004) suggested that the compositions of the aerosol particles and their concentration variations can invigorate the convection. On the other hand comparing the electrification of convective cloud for polluted and clear conditions Williams et al. (2002) suggested that the aerosols effect on CG lightning activity is not clear. So, there is no consensus on the effect of pollution on the CG lightning activity. The reason is due to the complexity of the phenomena. Hence extensive studies from different regions of the globe can resolve the issue. Most of the studies on lightning and thunderstorm have been carried out in the United States and in tropical areas. But the number of research work on lightning related to the areas like Taiwan is limited (Liou and Kar, 2010). As far as our knowledge is concerned no attempt has yet been made to investigate the urban effect on lightning activity over any region of Taiwan. In this paper, a 6-year climatological analysis of lightning data was conducted over and surrounding places of Taipei (25° 02′ 51″ N; 121° 31′ 54″ E), the capital of Taiwan, which is the 16th most densely populated country in the world with an average population density of 642/km^2 (1664/miles^2). In Taipei 9600 people live in every square kilometer. The urban area of Taipei City is approximately 271.8 km^2 and is similar to Houston in that both are coastal cities. Flash density of both polarities and the percentage of positive flashes have been calculated. The results are presented and compared to those available in the literature.

2. Data and methodology

For the present study we have collected lightning data from Tai-Power Company of Taiwan for the years 2005–2010 to determine the urban effect on lightning over Taipei and its surroundings places. The Lightning Location System (LLS) was built in 1989 with one APA (Advanced Position Analyzer), and six Direction Finders (FD) installed at sites covering the entire area of Taiwan. The LLS was upgraded to a Total Lightning Detection System (TLDS) in 2002. The TLDS consist of seven lightning detection sensors (SAFIR 3000), which are located at the top of Ying-Tsu-ling microwave tower, Wu-shih-pi microwave tower, Ji-shan microwave tower, Nan-Ke extra voltage substation, Feng-Lin microwave tower, building roof of Ming-Tan power plant, and building roof of Xiao-liou-chiou. The location of these seven sensors, distributed throughout Taiwan, is shown in Fig. 1. VHF interferometric technique is the main basis for the localization principles of SAFIR network (Richard and Auffray, 1985; Richard et al., 1986). The seven lightning detection sensors, formed a lightning detection network, could detect cloud-to-ground lightning discharges, cloud lightning discharges, and breakdown events. The lightning discharges detection is accomplished through the use of multiple, remote sensors that detect signals emitted by lightning discharges, and by filtering out the signals from non-lightning sources. The Long rang localization of all lightning discharges (CG and CC lightning flashes) is governed by triangulation performed on GPS time synchronized direction of arrival provided by interferometric sensor of two different detection station in a SAFIR network. Each sensor detecting a lightning event sends data about that event to a central processor (SCM) that triangulates the results from each sensor creating an optimal estimate of location of the lightning event. The lightning detection network average efficiency is greater than 90%, and the lightning detection localization accuracy is less than 1 km. However, especially near the edges of the network the assumption of more than 90% uniform flash detection efficiency may not be realistic, but because of comparatively higher average detection efficiency and localization accuracy no attempt was taken to correct the detection efficiency because previous studies (e.g. Naccarato et al., 2003 for a Lightning Position and Tracking System (LPATS); Orville, 1994 for the National Lightning Detection Network in the United States; Finke and Hauf, 1996 for a LPATS in Germany, and Pinto et al., 1999 for a LPATS in Brazil) reported an overall detection efficiency of 90% for several lightning detection networks.

Air pollutant data were collected from a well organized air quality-monitoring network operated by Taiwan Environmental Protection Administration. Taiwan's air quality monitoring network measures PM10 concentrations by the automatic Wedding β-gauge monitors, which is one of the US EPA-designated equivalent methods (no. EQPM-0391-081). For the present study PM10, SO_2 over Taipei County are considered.

For ease in computation we have considered blocks corresponding to upwind, over and downwind areas of Taipei City. A spatial scale of approximately 0.08° latitude × 0.08° longitude has been chosen as grid box. The area enclosed by a grid box is ~8.8 km × 6.6 km–58 km^2. Hence, each block associated with upwind, over and downwind comprises 6 grid boxes. The whole urban area of Taipei is covered by such 6 grid boxes. In the next step the numbers of CG flashes are counted within the blocks assigned for upwind, over and downed area. The computed results are then compared to analyze the urban effect on CG lightning activity. Such procedure was adopted by Westcott (1995). The blocks corresponding to upwind and downwind areas are selected based on the strong prevailing wind motion. Taiwan has a clear southwesterly component of its warm season prevailing wind motion (Chen et al., 1999). Hence, upwind (downwind) areas are located to the southwest (northeast). In calculating the urban CG lightning flash density, we have counted the number of CG flashes in block, which covers the whole urban area of Taipei City. But for the computation of lightning flash density for upwind and downwind areas, we have

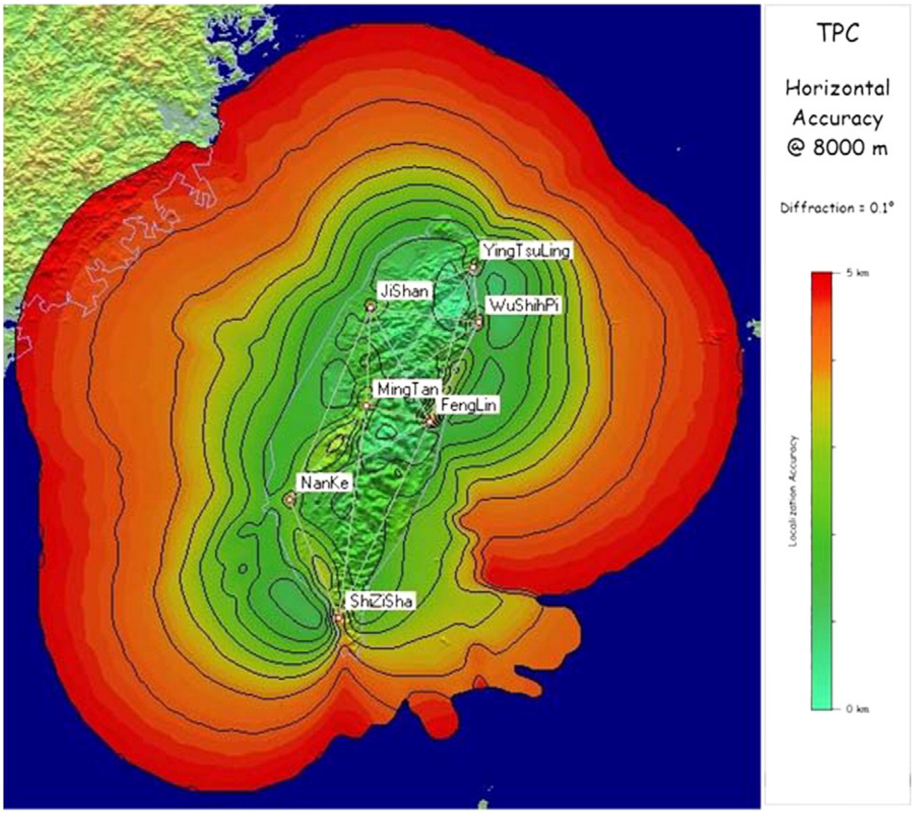

Fig. 1. Location of the sensors used in the Total Lightning Detection System (TLDS) of Tai-Power Company, Taiwan.

selected three blocks for each area. These blocks are located to the west, south-west, south, north, northeast and east of Taipei City. Then the total number of CG flashes over upwind or downwind areas is counted by taking the mean of the three southwest and northeast blocks, respectively. The number of flashes within the urban area is then compared to that of the flashes in the upwind and downwind areas. Similar method is adopted for the calculation of negative flash density, positive flash density and the percentage of positive flashes for upwind and downwind areas. Lightning flashes are counted for equal number of grid boxes with urban area but in upwind and downwind areas adjacent to Taipei City, which covers nearly the equal area of total urban area. The number of lightning flashes in each block is counted for a six-year period and then averaged. Needless to say that special emphasis to the polarity of lightning flashes has been paid in calculating the flash densities of both polarities and the percentage of positive flashes. Taking the difference in the average flash density between a particular region and its neighboring region and dividing the results by the average flash density of the neighboring region and finally multiplying the number by one hundred, percentage increases are calculated.

3. Results and discussion

Fig. 2 represents the geographical distribution of the mean annual negative flash density over Taipei and nearby areas. A significant enhancement of 64% negative flash density is noticed over and downwind of the city. This value is bit larger than that reported by Steiger et al. (2002), but lower than that reported by Westcott (1995) and Pinto et al. (2004). The warm season prevailing winds over Taiwan have a clear southwesterly component and, hence, upwind (downwind) areas are located to the southwest (northeast). Spatial distribution of mean annual positive flash density is displayed in Fig. 3. In this figure a significant enhancement is still visible. An enhancement of approximately 48% is found positive flash density over and downwind of the city, compared to the nearby surrounding areas. This value corroborates well the results reported by Westcott (1995) and Pinto et al. (2004). Taking the total enhancement into consideration, an average enhancement of 56% is observed. This value is close to the value (45%) reported by Steiger et al. (2002) but considerably lower than the value (85%) reported by Pinto et al. (2004). Taipei is located in a basin which is surrounded by low hills to its southwest and taller mountains in all other directions. Two river valleys, formed by Tanshui River in the northwest and the Keelung River in the northeast, carry surface airflow to the open sea. Such a complex geographic and orographic structure makes the Taipei urban region a unique environment among large cities around the globe. The interaction of surface airflows within the Taipei basin is limited by the complex geographic/orographic structure with the open sea only through these two river valleys. Again the surface winds at both river valleys are regulated by the alternation of the land–sea breeze. Cooler moist air is transported into the Taipei basin by sea breezes

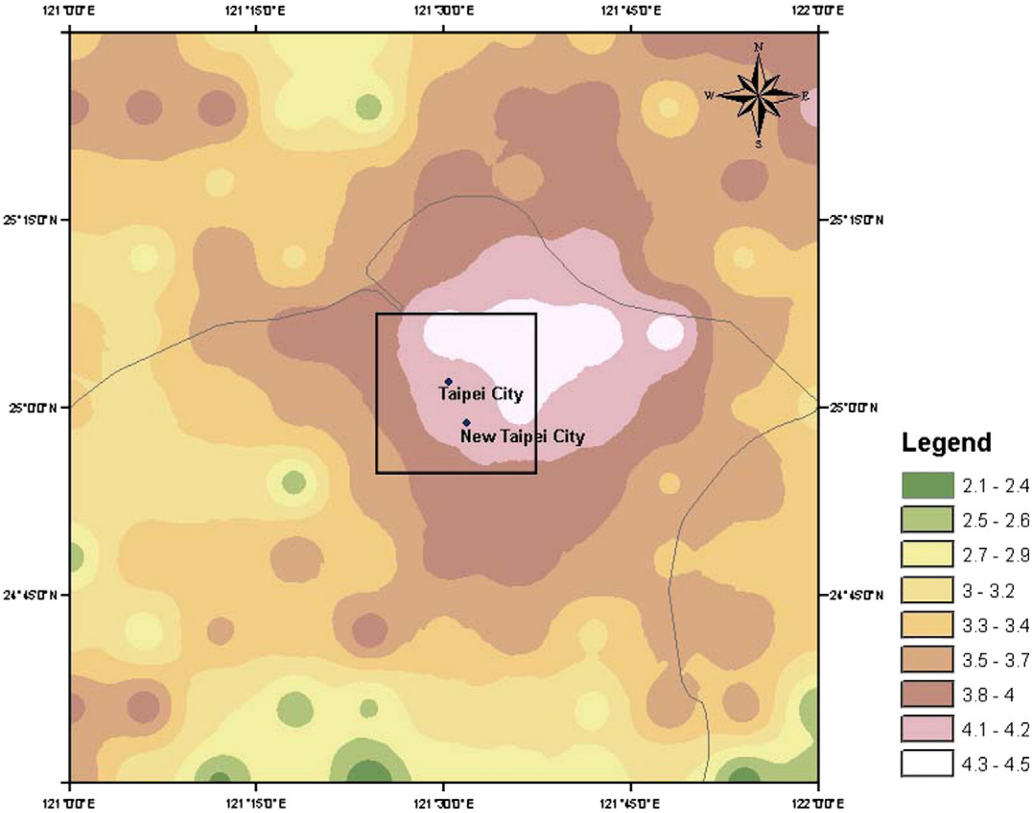

Fig. 2. Geographical distribution of the negative lightning flash density (fl km^{-2} yr^{-1}) centered on Taipei City.

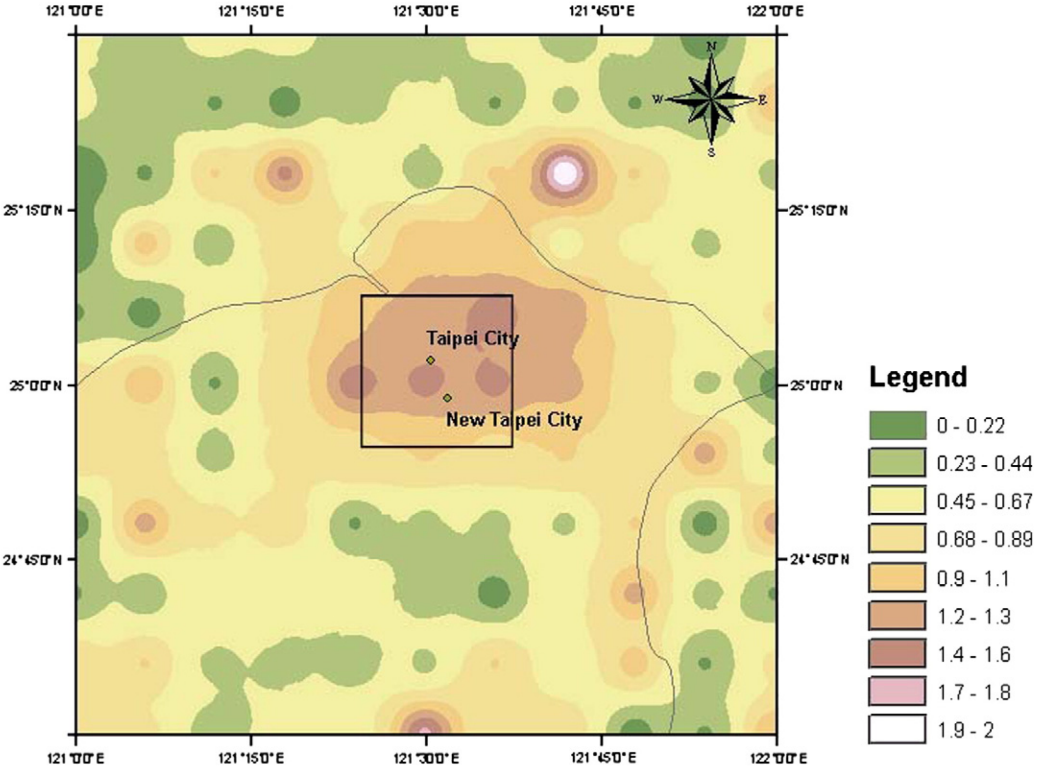

Fig. 3. Geographical distribution of the positive lightning flash density (fl km^{-2} yr^{-1}) centered on Taipei City.

through the Tanshui and Keelung River valleys (Chen et al., 1999). This sea air, after being warmed by the urbanized Taipei basin, is then converged toward the mountains bordering the northeastern basin. Thus, lightning genesis is supposed to be enhanced by the warm moist sea air downwind of the Taipei urban heat island.

Fig. 4 shows the geographical distribution of the percentage of positive flashes over Taipei and surrounding areas. An approximate decrease of nearly 17% in the percentage of positive flashes occurs over and downwind of Taipei. Steiger et al. (2002) and Pinto et al. (2004) reported a decrease of 12% and 25%, respectively, in the percentage of positive flashes compared with downwind areas. So our result strongly supports the previous findings. Such decrease in percentage of positive flashes can be explained from cloud microphysical processes of charge separation. Jayaratne et al. (1983) found that the graupel target charged negatively for all temperatures (−6 °C to −25 °C) after impurities are placed in the cloud. If the droplets contained a small amount of the most commonly available natural contaminants, the charge reversal temperature of −25 °C is shifted to higher temperatures. At low temperatures it is negative; at higher temperatures it is positive. Occurrence of such negative graupel charging due to increased impurities in the cloud water at higher temperatures can stretch the region of main negative charge lower to the cloud, covering the positive charge center below (Pruppacher and Klett, 1997). The newly stretched region of negative charge of the thunderstorm tripolar charge distribution model (MacGorman and Rust, 1998) may generate more negative CG flashes, decreasing the relative frequency of positive flashes. In contrary to the above hypothesis, Avila et al. (1999) found that the target graupel is charged positively over most of the temperature range (−10 °C to −25 °C) and charged negatively at temperatures below −18 °C for smaller and larger droplet spectrum, respectively, during ice–ice collisions in the presence of supercooled water. This suggests the existence of a deeper positive charge center in the lower region of a thunderstorm which in turn intensifies further the possibility of higher percent positive values over a polluted airmass or over an area favorable for the formation of a smaller droplet spectrum. Hence, an extensive analysis is required to resolve this ambiguity in explaining the lightning characteristics.

Geographical distribution of peak currents for both polarity over Taipei City and surrounding areas are shown in Figs. 5 and 6. Fig. 5 represents the variation of negative peak current while Fig. 6 shows the same for positive peak currents. From both the figures no significant effects of urban areas on peak currents are noticed except a slight decrease in the peak current of both polarities in the southern part of Taipei City, especially for negative flashes. This decrease in peak current may be attributed to the presence of the high altitude tip of the central mountain ridge of Taiwan. If the charge were accumulated evenly along the leader channel and the altitude of the charge center were lower in negative lightning than positive lightning, then both the lowering of charge to the ground and the corresponding peak current would be less. The relatively shorter lightning channels, expected to occur over mountainous region, could make

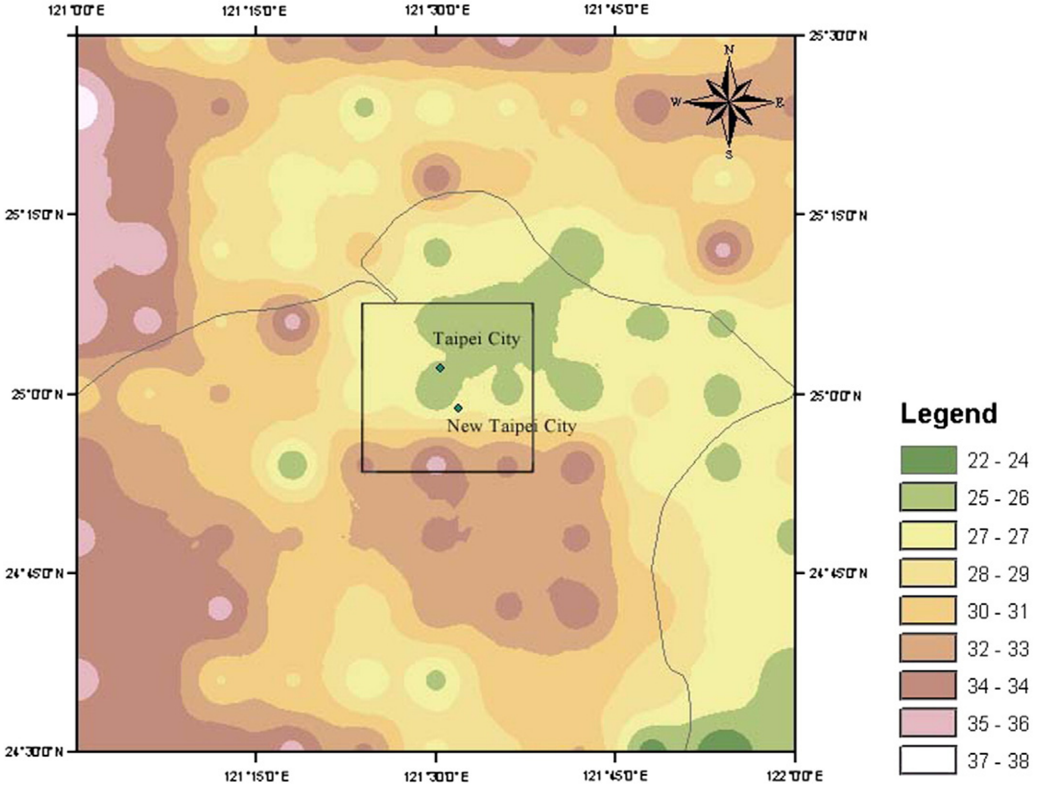

Fig. 4. Geographical distribution of the percent positive CG flashes centered on Taipei City.

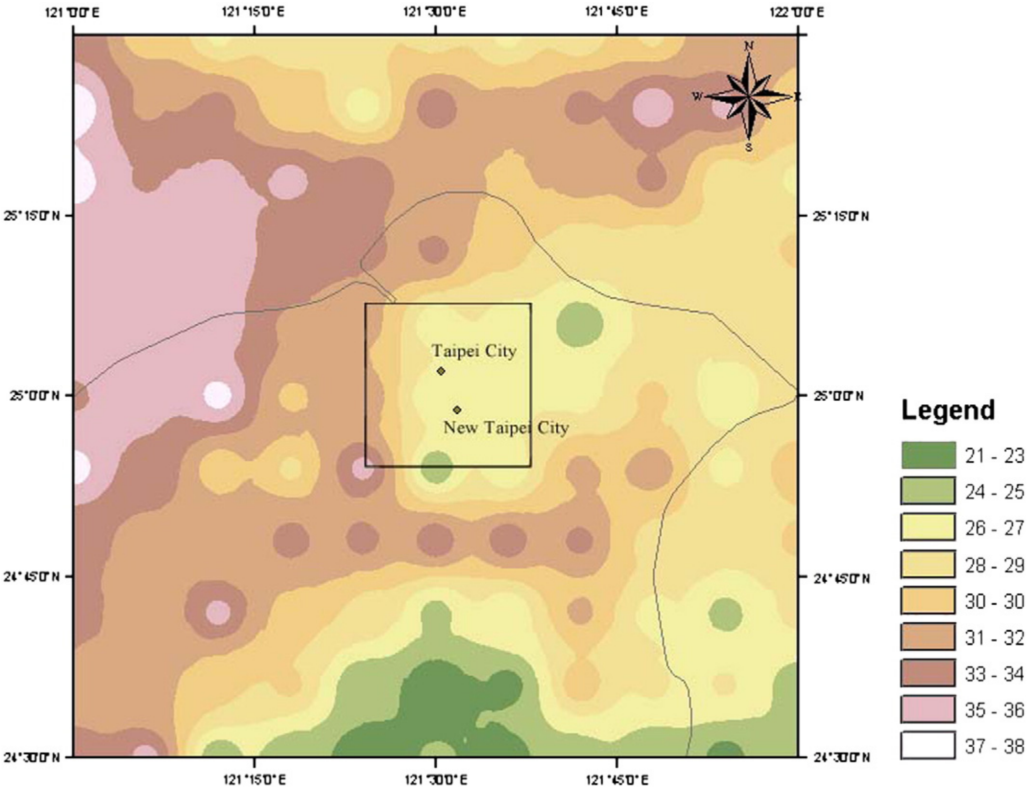

Fig. 5. Geographical distribution of the mean negative peak current (kA) centered on Taipei City.

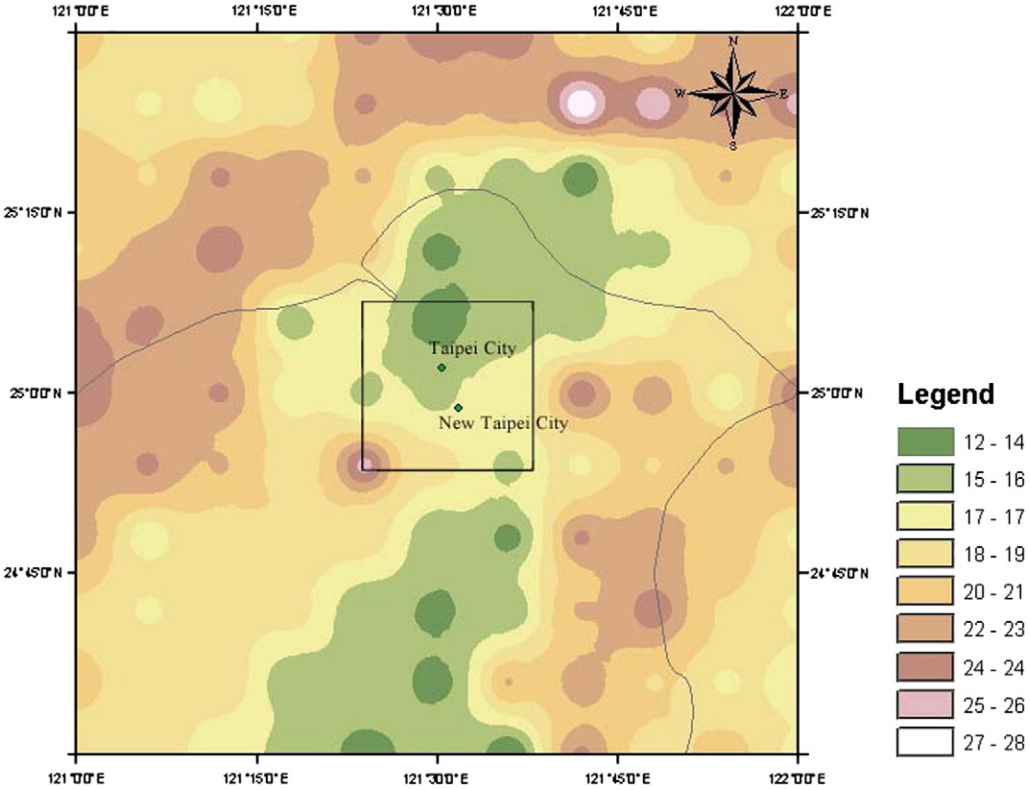

Fig. 6. Spatial distribution of the mean positive peak current (kA) centered on Taipei City.

another contribution to lower mean peak currents. However, the positive lightning arising from higher altitudes would be expected to exhibit less of an effect. The effect of high altitude on the lightning peak current was first reported by Reap (1986) and was supported by Orville and Huffines (1999) in their recently found observation. Slight higher value in the negative peak current in the western coast of Taipei City may be attributed to the higher conductivity of the underlying salt water of the China Sea. Lyons et al. (1998) and Steiger et al. (2002) suggested in their study that the underlying salt water of the Gulf of Mexico is associated with higher conductivity.

The annual averages of PM10 and SO_2 concentrations have been considered in relation to the percent change of CG flashes to investigate the possible relationship between urban particulate matter and CG lightning activity. We have assumed the concentrations of PM10 and SO_2 to be gross indicators of the CCN concentrations. Because of convenience PM10 data have been chosen as a proxy for urban polluted air. Fig. 7 shows the scatter plot of CG lightning change with PM10 concentrations. Positive correlation between the two plotted parameters is clearly observed in Fig. 7 indicating a close association of percent change in CG flashes from upwind to the urban area and from upwind to the downwind area with PM10 concentration. However, the correlation coefficient is not as strong as found in the latter case of SO_2 concentrations which has been shown in Fig. 8. Scatter plot of SO_2 concentrations with percent change in CG lightning flashes is displayed in Fig. 8. As before, in the case of SO_2 also a positive correlation is found between the SO_2 concentrations and the percent change in CG lightning flashes from upwind to the urban area and from upwind to the downwind area. These results indicate a possible influence of urban aerosol concentrations on the number of CG lightning flashes. Hence, it may be concluded that increased concentration of SO_2 contributes in enhancing the CG flashes but the increased PM10 concentration does not seem to be as influential a parameter as SO_2 to the enhancement in CG lightning flashes as is evident from their correlation coefficient. 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 sulfate particles are usually more active in the formation of cloud droplets compared to PM10 (Seinfeld, 1975), a slightly 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 Westcott (1995), but corroborate well with the results of Soriano and Pablo (2002). Westcott (1995) has found that large annual values of SO_2 and PM10 correspond generally to the large values of urban and downwind CG flash. Hence, data from other geographical locations and for more years are required to resolve this diversity in findings. Correlation coefficients between PM10 concentrations and the change in the number of CG flashes from upwind to urban and from upwind to downwind areas are found to be 0.31 and 0.55, respectively, while the correlation coefficients between SO_2 concentrations and the change in the number of CG flashes from upwind to urban and from upwind to downwind areas are found to be 0.53 and 0.68, respectively. All the correlation coefficients are significant at the 99.9 confidence level.

Interaction between the urban heat island and the unstable air flowing over it may extend the radar echoes to greater heights over the urban and downwind areas during the afternoon hours has been suggested in several studies (e.g. Braham and Wilson, 1978). For the existence of such speculation, warm season hourly average flash count was computed for Taipei City to investigate whether such effect also occurs in the CG lightning data. Fig. 9 shows the hourly average flash count variation CG flashes over Taipei City. An escalation in the average number of flashes over the urban and downwind areas is distinctly visible. The enhancement is prominent during 1200 to 2000 local standard time (LST) with a maximum around 1400 and 1600 LST for downwind and urban areas respectively, indicating that the

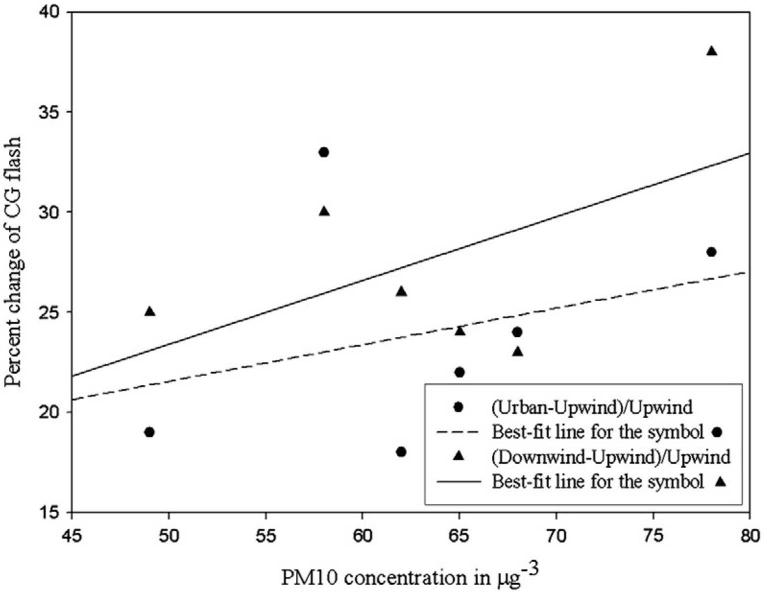

Fig. 7. Scatter plot of percent change of CG flashes and annual averages of PM10 concentrations for the year 2005–2010.

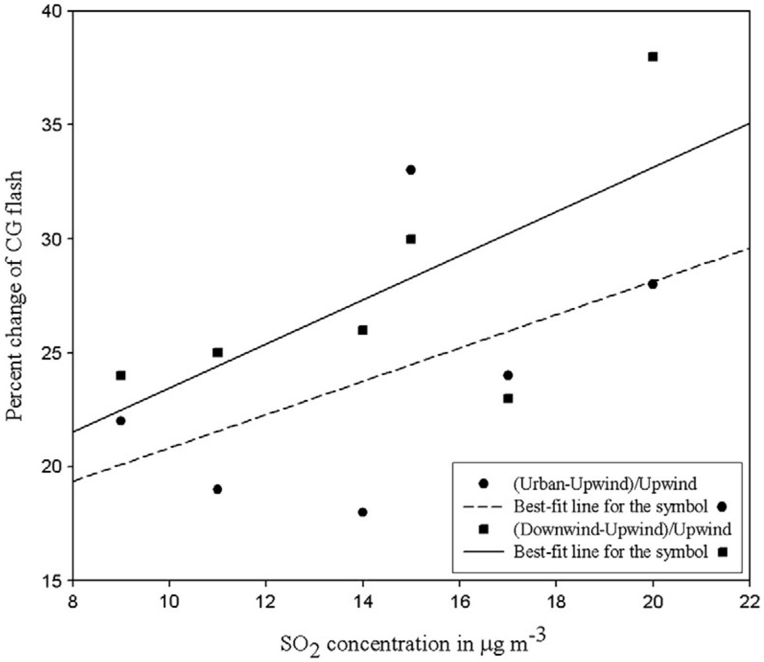

Fig. 8. Scatter plot of percent change of CG flashes and annual averages of SO$_2$ concentrations for the year 2005–2010.

urban effect on CG lightning activity is focused in the afternoon and early evening. The two major river valleys are the main gateway through which the sea breezes from China Sea are channeled toward the Taipei basin. These sea breezes interact with the down slope flows from the mountains and produce a strongest upward motion because of the destabilizing effect on the local atmosphere caused by Taipei urban heat island. Intensification of the urban heat island and sea-breeze circulation possibly influences the afternoon/evening lightning peak activities inside the Taipei basin. Therefore, it can also be inferred from Fig. 9 that the urbanization tends to anticipate the daily lightning peak activity over Taipei urban area. This result agrees fairly well with the findings of Westcott (1995), who reported significant increase in lightning over the urban areas during the afternoon and early evening in eight of the 16 large cities she examined in the United States.

4. Conclusions

In this paper, extensive long-term climatological analyses have been performed over Taipei, the capital city of Taiwan, taking lightning data from Tai-Power Company for the years

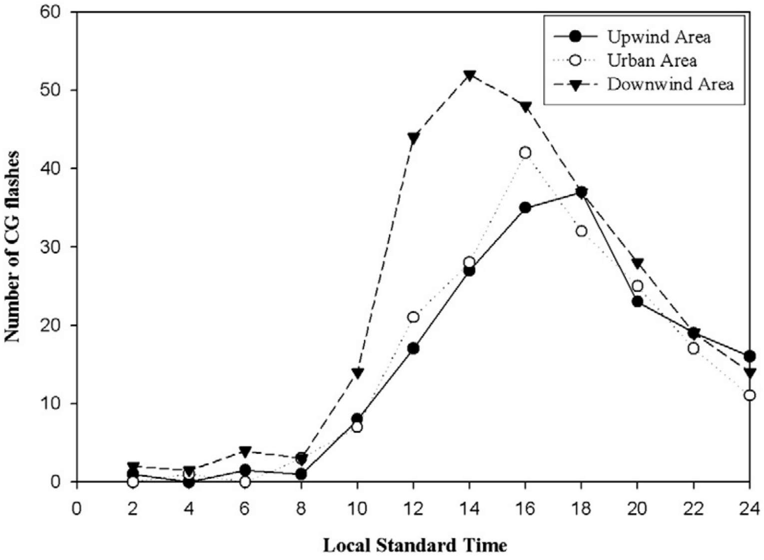

Fig. 9. Two hours averaged time plot of the number of CG flashes over the upwind, urban and downwind areas for Taipei City.

2005–2010 to investigate the urban effect on lightning production. Results reveal a significant increase of nearly 64% and 48% in the negative and positive flash densities, respectively, over and downwind of Taipei City compared to its nearby surrounding places. This study also indicates that a considerable 24% decrease in the percentage of positive flashes occurs over and the downwind of the city compared with upwind area. The results are in good agreement with those obtained by Steiger et al. (2002). However the present study does not indicate any notable urban effect on the peak current of both polarities, supporting the results obtained in Houston and Bole Horizonte. A positive linear correlation is found between the percent change of CG flashes from upwind to the urban area and from upwind to the downwind area, and a higher concentration of both PM10 and SO_2. These positive correlations clearly indicate a possible link between aerosol concentrations and enhancement of CG lightning flashes. Positive correlations of 0.55 and 0.68 are found for the PM10 and SO_2 concentrations, respectively, when compared separately with the percent change of CG flashes from upwind to the downwind area. 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. This higher positive correlation strongly supports that the aerosols play a key role in the enhancement of lightning activity over Taipei, 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. However, Lal and Pawar (2011) have not found any aerosol effect on lightning activity particularly over coastal cities while they have found the aerosol effect over inland stations. Very recently Farias et al. (2014) conducted a long term study of aerosol effect on the weekly cycles in lightning activity over Sao Paulo and reported that pollution tends to saturate the intensification of storm and lightning activity in a specific level. 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 among 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. Hourly variations of CG lightning has also been examined to investigate the possible hourly variations in the urban effect on CG lightning. It has been found that the pronounced enhancement in the CG lightning is occurred during 1200–2000 LST periods, when the lower atmosphere is expected to be highly unstable and convective development is also more probable as well. It is worth mentioning in this context that more than 90% detection efficiency especially near the edges of the network may not be realistic and may affect our result to some extent. Therefore the results presented here could be considered as representative.

Acknowledgments

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