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# Lightning ground flash patterns over Paris area between 1992 and 2003: Influence of pollution?

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12 summers of cloud-to-ground (CG) lightning flashes data over a 200 km×200 km domain centered on Paris (France) have been analyzed to infer the possible influence of pollution on lightning activity. Lightning flashes densities are calculated on a 5 km×5 km grid, filtered for discarding extremely high events, and differentiated from weekdays to week-end days, with a specific insight upwind, over, and downwind Paris. Lightning flashes are more numerous in the North-East part of the domain and increasingly large events progressively concentrate over Paris and over some hills around. The former result indicates a possible influence of pollution on lightning activity downwind of Paris; the latter probably illustrates the influence of the urban heat island and of the relief on the convection strengthening. Furthermore, the number of positive CG flashes is rather uniformly distributed on the whole domain, except in the North-East where it appears somewhat relatively lower meanwhile negative CG are relatively more numerous in that region. This corresponds to a reduction in the percentage of positive CG downwind of Paris. Additionally, lightning activity appears weaker downwind of Paris during weekend days. A specific daily analysis of the lightning density in circles distributed along the direction of prevailing wind through Paris shows that the lightning activity appears higher downwind during the days most worked as Tuesday, Wednesday and Thursday. This higher electric activity persists up to about 40 km on Wednesday, and up to about 80 km on Tuesday and Thursday (most days worked). The electrification seems therefore more important downwind of Paris during the more polluted days.

## 1. Introduction

Among the various influences that anthropogenic emissions may have on local and regional meteorology, the one that involves aerosols and cloud physics via the droplet spectrum appears very complex, especially when thunderclouds and electrification are considered (Mossop and Hallett, 1974; Rosenfeld and Lensky, 1998; Williams et al., 1999; Bell et al., 2008). As a matter of fact, lightning activity is supposed to be affected by several parameters that can reinforce the

convection like the sensible heating in response to solar radiation, the relief, the urban heat island (UHI), the wind convergence... However, these parameters can be in competition with the aerosols for lightning enhancement (Williams et al., 2004). The aerosols can even be key parameters according to several observations over cities where an increase in CG density and a decrease in positive CG percentage were detected (Orville et al., 2001; Areitio et al., 2001; Steiger et al., 2002; Naccarato et al., 2003; Pinto et al., 2004; Stallins et al., 2006; Kar et al., 2009), or under the influence of smokes emitted by biomass fires resulting on contrary in an increase in the positive CG percentage (Lyons et al., 1998; Murray et al., 2000; Lang and Rutledge, 2006). Furthermore, the triggering and the propagation of discharges could also be affected by

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pollution, which governs the electric conductivity of hydrometeors that are involved in discharge processes (Boussaton et al., 2005).

As far as the influence of aerosols on microphysics is concerned, the usual hypothesis put forward is that of Rosenfeld and Lensky (1998) and Williams et al. (1999). The so-called aerosol hypothesis is detailed and illustrated in Williams et al. (2002) and Rosenfeld et al. (2008). According to it, the increase in the number of cloud condensation nuclei (CCN) originated from a dirty continental boundary layer induces the multiplication of small droplets that share the available liquid water in the storm updraft. Subsequently, the coalescence process is less efficient because of a lack of mean droplet size. Therefore, more cloud water can reach the mixed phase region where droplets participate on one hand to the strengthening of the convection by the release of latent heat during their freezing, and on the other hand to the growth of graupel by riming and therefore to the charge generation process (see the review by Saunders, 2008). The electrification is thus enhanced by the presence of numerous CCN. However, the conclusion of this hypothesis is inconsistent with the part played by the Hallett-Mossop glaciation process. As described by Mossop and Hallett (1974) and by Mossop (1978), the secondary ice crystal production is sensitive to the drop size distribution and the presence of a high number of large drops is necessary. The release of CCN by anthropogenic activities tends to diminish the number of large drops and thus, to inhibit the Hallett-Mossop process. As this mechanism that provides high ice crystal concentrations is essential to cloud electrification (Hallett and Saunders, 1979), an increase in the number of CCN could produce a diminution in lightning activity. The question remains open.

The relationship between the lightning activity and all the parameters mentioned above is not clearly understood since it is most often difficult to isolate the influence of only one of them. Numerical models are not yet capable of analyzing real cases by taking into account kinematics, microphysics, aerosols, and electrical effects, together at high resolution. At the present time the French non hydrostatic mesoscale model Méso-NH (Lafont et al., 1998) can resolve convection at kilometer scale with an electrical scheme of electrification and lightning production (Barthe et al., 2005; Molinié et al., 2009). Beside, we dispose of the aerosol scheme of Tulet et al. (2005) but it does not apply to cloud interaction. CCN and ice condensation nuclei (ICN) are taken into account in a new scheme that is only currently under development. The other way is to perform long-term climatologic studies of CG lightning flashes that are expected to provide significant information on their average behavior. In order to assess the part played by pollution and UHI over a great urban center, we focused on the Paris area for which we dispose of 12 years of CG lightning data. We performed a progressive filtering of the CG density in order to identify the different zones where lightning flash activity is more and more intense. Moreover, following the approach of Dessens et al. (2001), who pointed out the day-of-the-week size variability of hail supposed to be due to the day-of-the-week variability of the aerosols distribution, we separated the CG distributions between week and weekend days.

After a presentation of the studied domain and of the CG data set, we present hereafter the overall results in terms of

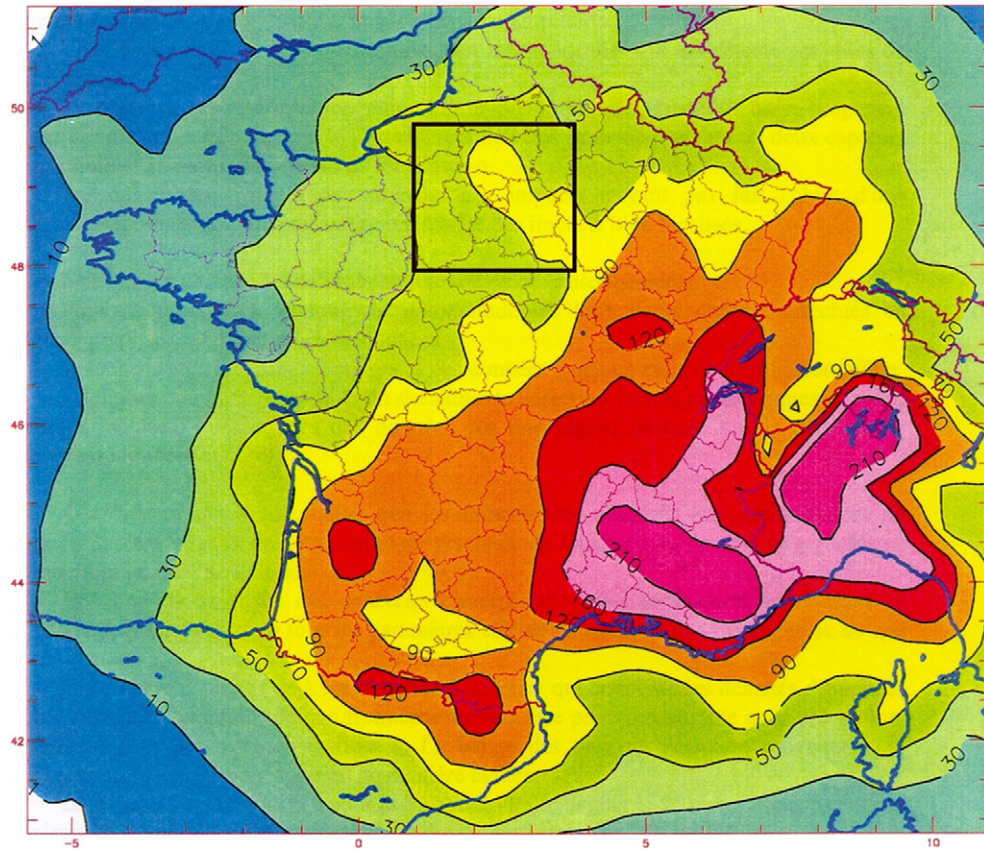
number of CG per day and per pixel and in terms of number of lightning days per pixel, for both polarities. Next, we describe the data filtering that appears to be a good tool for determining the location of the increasingly hot spots. We then discriminate the results between weekdays and weekend days and perform a daily analysis of the lightning activity distributed along the direction of prevailing winds through Paris. We finally discuss the influence of the various factors (relief, UHI, pollution) that could be at the origin of the observed CG features on the domain.

## 2. Domain and data descriptions

The studied domain is defined as a square area of 200 km  $\times$  200 km centered on Paris, the latitude and longitude of which are respectively 48.86° and 2.35° (see Fig. 1). The relief of the domain is displayed in Fig. 2, in which the boundaries of Paris city and of its surrounding built-up area are drawn in black lines and several main cities are mentioned with black circles. Located in the Seine valley, Paris is surrounded by several hills that are located close to the borders of the domain in the South-West, North-West, East, and South-East. One ridge North-West to South-East directed between Rouen and Beauvais appears closer to Paris. The maximum altitude on the domain does not exceed 325 m.

The region is usually submitted to a degraded oceanic climate characterized by frequent and generally weak precipitations. During the whole period considered in the present study, which extends from May to September (extended summer period) of 12 years from 1992 to 2003, the average monthly minimum and maximum temperatures in Paris city raised to about 13.9 °C and 23.0 °C, respectively (see Fig. 3). During the same period and in the same location, the number of days with a temperature greater or equal to 25 °C is about 53 on average but varies from 36 in 2002 to 82 in 2003. The latter year corresponds to a well known episode of heat wave. The wind is most often from West/South-West. For example, among the 26 high radar reflectivity storms that occurred during summer 2000 (see Boussaton et al., 2007) about 73% of them moved from the South-West to the North-East of the domain, meanwhile about 23% were involved in a South-East to North-West motion. In order to give a better idea of the wind characteristics during the studied period, the frequency distribution of the wind direction and speed at the 500 hPa level over Paris is plotted in Fig. 4 for the days when lightning were observed from May to September during only 8 years from 1996 to 2003 (data from Météo France – the French National Meteorological Service – were available since 1996), that is to say 66% of the lightning days considered in the whole study. Most of the speeds ranged from 5 to 25 m/s with a main direction from West/South-West.

The domain is also characterized by a strong urban activity, especially Paris and its suburbs that are source of anthropogenic pollution, with a strong industrialization and an intense traffic. An average temperature difference of several degrees is frequently detected between the center and the exterior of the city, which denotes the presence of an important urban heat island effect.

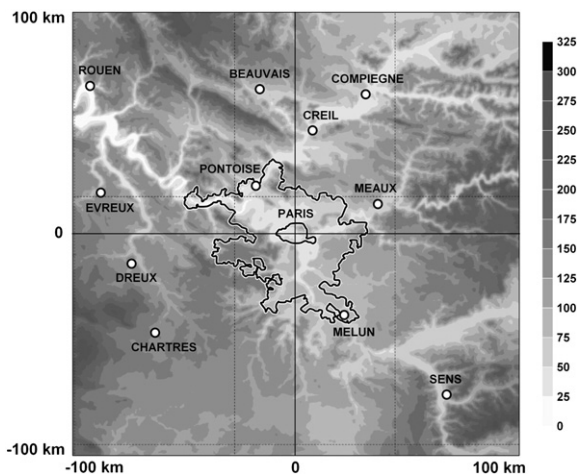


**Fig. 1.** Annual density of CG flashes by the Météorage network from 1988 to 1996 (adapted from Lassègues et al., 1997). The black square (centered on Paris) corresponds to the 200 km×200 km domain studied in present paper.

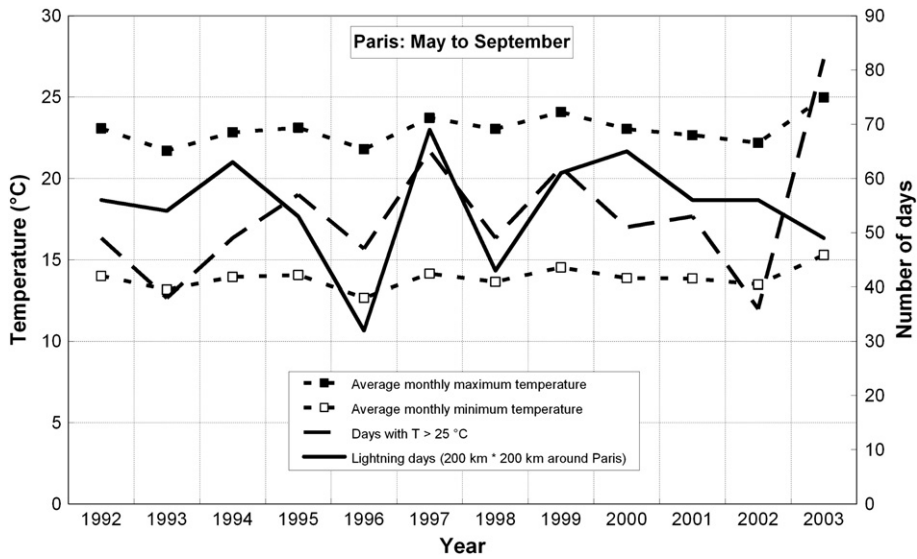
The lightning activity was observed by the French Météorage network which has been operating since 1987 and was upgraded in December 1996 with IMPACT sensors, in 1999 with a new localization algorithm, and year after year by the setting up of additional sensors in France and in

Belgium, Germany, and Switzerland. Using the Direction Finder (DF) and the Time-Of-Arrival (TOA) techniques, it provides for each CG flash the location of the ground impact, the occurrence time, the number of strokes, and the peak current of each stroke. Initially equal to about 4 km in average, the localization accuracy has gradually been reduced to about 1 km; and the detection efficiency is larger than 90% on most part of the French territory, except in some peripheral zones where it remains close to 70%.

The domain is divided into pixels of 5 km×5 km in which CG flashes are daily counted over the whole period. In the following, only the number of CG flashes per pixel and the number of days during which at least one CG flash occurred in a pixel are considered, since the continuous upgrade of the network does not allow to correctly analyzing the evolution of parameters such as peak current and multiplicity, which values are sensitive to the detection system. For example, between 1992 and 2003 the maximum peak current decreased from 64.4 kA down to 31.3 kA on average for positive CG and from 29.4 kA down to 20.6 kA on average in absolute value for negative CG. As it has become possible to detect lower and lower peak current discharges, this continuous upgrade undoubtedly induces a lessening of the average peak current. But there is no mean for determining if the observed decrease is totally due to this induced lessening or if pollution might have an impact on it.



**Fig. 2.** Relief in meters of the square 200 km×200 km studied domain centered on Paris. Paris city and its surrounding built-up area are delimited with black lines, and several main cities are displayed with open circles.

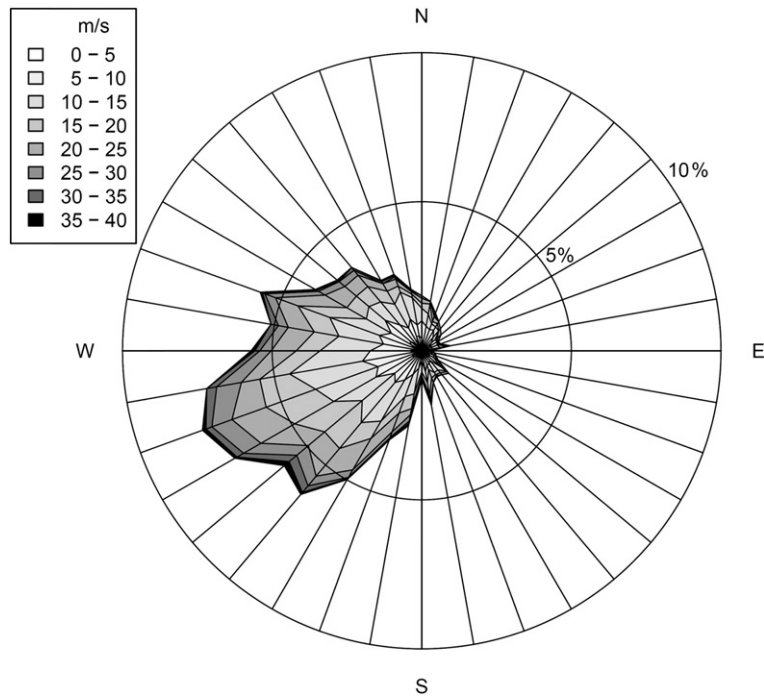


**Fig. 3.** Comparison of the number of CG lightning days in the whole domain during May to September from 1992 to 2003 (solid line) with climatic data of Paris city: average monthly maximum and minimum temperatures (dotted lines with black and open squares, respectively), and number of days when  $T > 25^{\circ}\text{C}$  (dotted line).  
Data from Météo France.

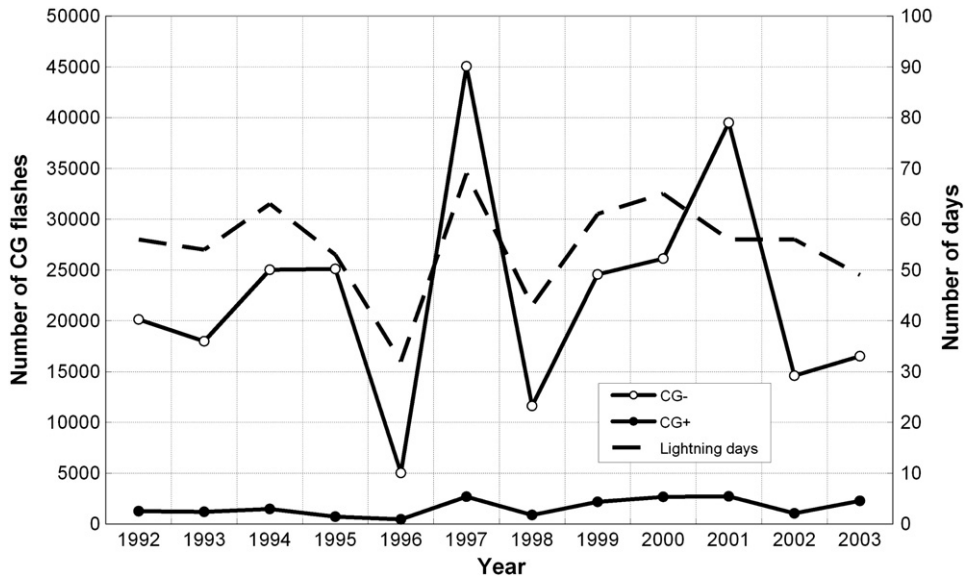
### 3. Overall results

Throughout the observation period of 1836 days (1311 week days and 525 weekend days), 290,780 CG flashes were detected in the studied domain during 657 days (about 36% of the

observation days) homogeneously distributed in 467 week and 190 weekend days (220,925 and 69,855 flashes, respectively). The year by year evolution of the number of lightning days is displayed in Fig. 5. It evolves between a rather low minimum of 32 in 1996 and a maximum of 69 in 1997. As a matter of fact,



**Fig. 4.** Frequency distribution of wind direction and speed at the 500 hPa level over Paris for the days when lightning were observed from May to September during only 8 years from 1996 to 2003.  
(Data from Météo France).



**Fig. 5.** Number of negative CG (solid line with open circles), positive CG (solid line with black circles), and lightning days (dashed line) in the whole domain during May to September from 1992 to 2003.

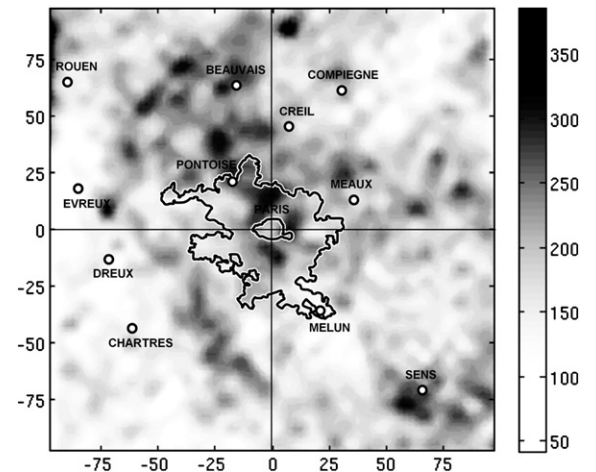
1996 exhibited a fairly cold summer with a relatively low number of days when the temperature was greater than 25 °C, and with the lowest average monthly maximum and minimum temperatures (see Fig. 3). Consequently, the lightning activity is logically weak this year. As far as 1997 is considered, the maximum of the number of lightning days is associated to rather high average monthly minimum and maximum temperatures, but more especially to the highest number of days with temperature larger than 25 °C if 2003 – year of the well known heat wave – is disregarded.

Among the whole set of flashes, 271,232 (93.3%) were negative CG with an average multiplicity equal to 2.2 and 19,548 (6.7%) were positive CG with an average multiplicity equal to 1.11. If we disregard the positive discharges with peak currents less than 10 kA that should be regarded as cloud discharges as suggested by Cummins et al. (1998), the percentage of positive CG is lowered to 6.3% (1217 cloud discharges would have been detected mainly between 1997 and 2003 in an increasing way). From 1992 to 2003, the percentage of positive CG slightly increases with an average rate of 0.25 points by year if the so-called cloud discharges are disregarded (0.39 if not).

Fig. 5 shows the evolution of the number of negative CG and positive CG, which appear to be fairly well time-correlated with the number of lightning days, except in 2001 where the number of CG is relatively high, and in 2002 where it is relatively low. As a matter of fact, an exceptionally active storm that took place in 26 July 2001 is probably at the origin of that discrepancy in 2001. However, another very large event that took place on 14 May 1998 does not seem to have the same influence in the corresponding year, maybe because the number of CG was twice lower than that of 26 July 2001.

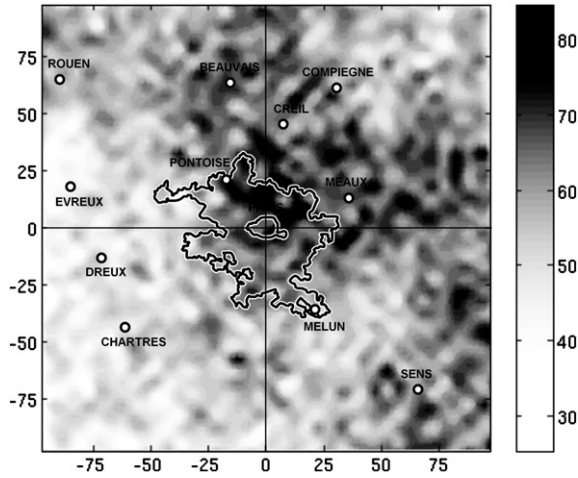
The distribution of the total number of CG flashes is displayed in Fig. 6, in which the boundaries of Paris city and of its surrounding built-up area are drawn in black and several main cities are mentioned with black circles. This

distribution exhibits a general pattern somewhat equivalent to that observed in this region between 1988 and 1996 by Lassègues et al. (1997), as shown in Fig. 1, with a minimum of activity in the South-West part and in the North-East corner of the domain. Though, two trails of high activity that correspond to the very large events of 14 May 1998 and 26 July 2001 clearly stand out. The influence of both events on the distribution of the total number of CG flashes is quite obvious if we compare it to the distribution of the number of lightning days displayed in Fig. 7, in which both trails disappear. This confirms that each trail corresponds to only one day of very high lightning activity. Consequently, this observation raises the problem of the statistical meaning of the data, as pointed out by Gauthier et al. (2005). Therefore, a



**Fig. 6.** Total CG flashes per pixel (5 km × 5 km) over the whole period during May to September from 1992 to 2003.



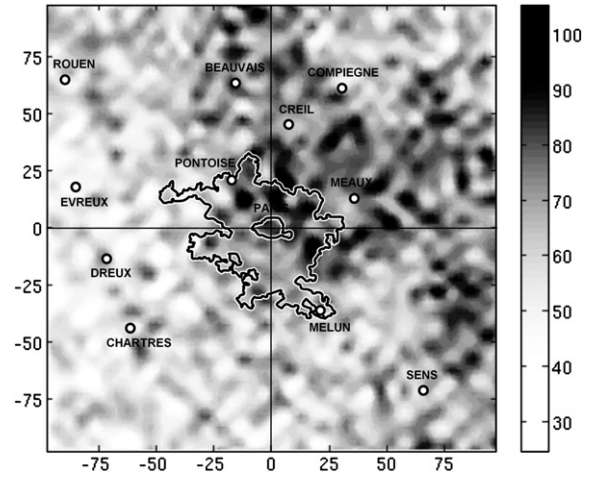


**Fig. 7.** Total lightning days per pixel ( $5 \text{ km} \times 5 \text{ km}$ ) over the whole period during May to September from 1992 to 2003.

specific filtering is required to make this kind of event vanishing.

#### 4. Data filtering

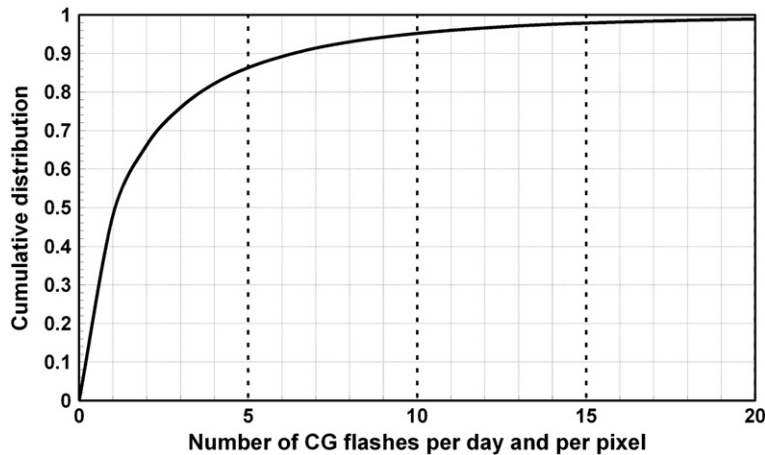
In order to improve the statistical meaning of the data, we applied the method by Gauthier et al. (2005) to filter the large event days. Given the daily flash count distribution for each pixel, statistics are used to classify the large event days as follows: they correspond to the days the flash count of which exceeds the 75th percentile of the cumulative distribution for all days and all pixels (see Fig. 8). The third quartile (Q3 corresponding to 3 flashes per day and per pixel) is thus the threshold beyond which any event in a given pixel is classified as large event day and is therefore disregarded in the data set. The distribution of the total number of CG flashes per pixel filtered according to this method is displayed in Fig. 9. The comparison with the unfiltered distribution displayed in Fig. 6 shows that the very large events of 14 May 1998 and 26 July 2001 correctly vanish, and that the filtered distribution



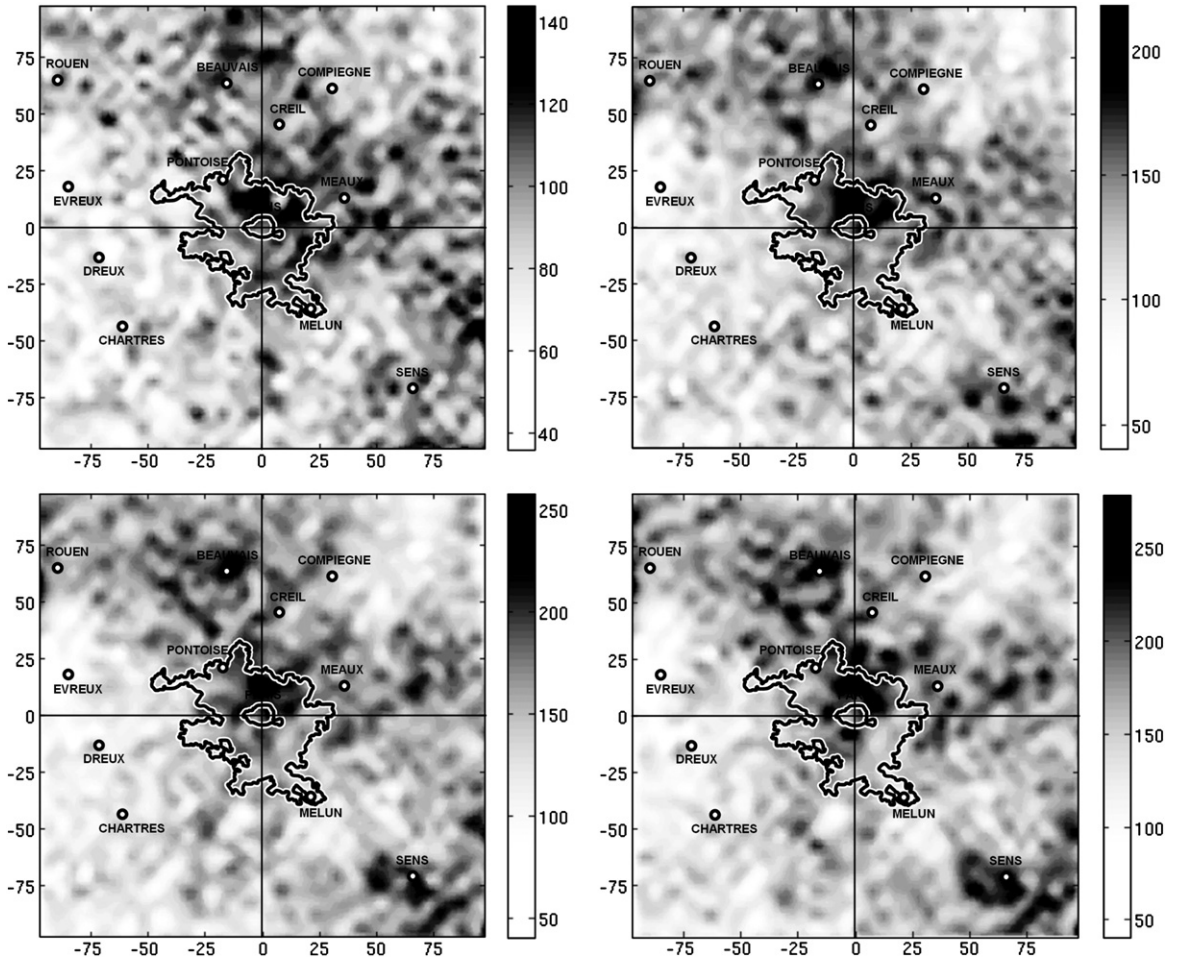
**Fig. 9.** Total CG flashes per pixel ( $5 \text{ km} \times 5 \text{ km}$ ) over the whole period during May to September from 1992 to 2003 for a maximum number of flashes per day and per pixel equal to 3.

is in good agreement with the distribution of the number of lightning days displayed in Fig. 7. It displays a maximum of CG flashes over Paris city and especially over the North, North-East, and East surrounding built-up areas, and also on the North, East, and South-East parts of the overall domain. On the contrary, the West part of the domain is much less affected by CG flashes. These summer features are in good agreement with the observations by Lassègues et al. (1997) that correspond to annual data (see Fig. 1). This puts forward that the lightning distribution over Paris is mainly affected by summer events, as expected.

Furthermore, we also analyzed the CG flash distribution by gradually filtering the data with an increasing threshold of flash per day and per pixel. This procedure allows identifying the locations where more and more active thunderstorms occurred. The total number of CG flashes has been computed with thresholds equal to 5, 10, 15, and 20 flashes per day and per pixel. The results are displayed in Fig. 10 and can be compared with the distributions corresponding to a threshold equal to 3 (Fig. 9), and to an infinite threshold (Fig. 6).



**Fig. 8.** Cumulative distribution of the number of CG flashes per day and per  $5 \text{ km} \times 5 \text{ km}$  pixel.



**Fig. 10.** Total CG flashes per pixel (5 km  $\times$  5 km) over the whole period during May to September from 1992 to 2003. The maximum number of flashes per day and per pixel is 5 (top left), 10 (top right), 15 (bottom left), and 20 (bottom right). For a maximum number of flashes per day and per pixel equal to 3 see Fig. 9. For an unlimited number of flashes per day and per pixel see Fig. 6.

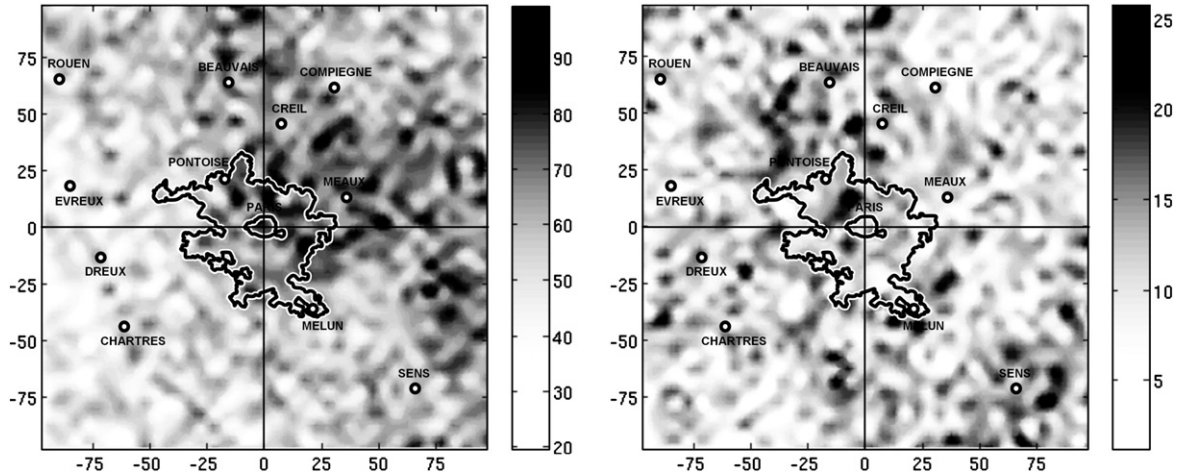
One can point out that relative maxima progressively concentrate mainly over the North/North-East close suburbs of Paris, over Beauvais and its South-West region, over Sens in the South-East part of the domain, an over the East part of the domain. Most of these locations correspond to relatively elevated hills, except Paris suburbs. It must be pointed out also that other secondary maxima concentrate over the West and South boundaries of Paris city when the largest thresholds are considered.

If we compare more in detail the relief (Fig. 2) and the total CG flash distribution corresponding to a rather high filtering threshold, one can identify some spatial coincidences of fine structures of the relief with rather high lightning activities. For instance, considering a threshold of 15 lightning per day and per pixel (i.e. only 2% of the highest events are disregarded, see Fig. 8) allows to clearly outline the following patterns (see Fig. 10, bottom left). The windward zones of the main ridge North-West to South-East directed between Rouen and Beauvais and of the secondary ridge, parallel to the main one, located tens of kilometers at the North of it and very close to Rouen, seem associated with high lightning activity lines.

The same pattern can be pointed out along the uphill slope of the South bank of the Marne River, which meanders between Paris and the East/North-East of the domain. Another salient feature concerns the high lightning activity line that matches rather well to the Oise River valley, which passes by Pontoise, Creil, and Compiègne in the North of Paris.

As far as lightning polarity is considered, we computed the filtered flash densities of negative and positive CGs, which are displayed in Fig. 11 for a maximum of 3 CG flashes per day and per pixel. For negative CG flashes (left), the distribution is similar to that corresponding to all CG flashes (see Fig. 9) since a great majority (93.3%) of the CG flashes observed are negative ones. By comparison, the positive CG flashes (Fig. 11, right) are more uniformly distributed on the whole domain since they are most often produced in the spread stratiform region of thundercells. However, they appear relatively less numerous than expected in the North-East quarter of the domain if we consider that this quarter is the most active one when all CG flashes are considered (see Fig. 9). This pattern of the positive CG flashes distribution remains unchanged whatever the level of filtering is.





**Fig. 11.** Total negative CG (left) and positive CG (right) flashes per pixel (5 km  $\times$  5 km) over the whole period during May to September from 1992 to 2003 for a maximum number of flashes per day and per pixel equal to 3.

## 5. Week to weekend differentiation

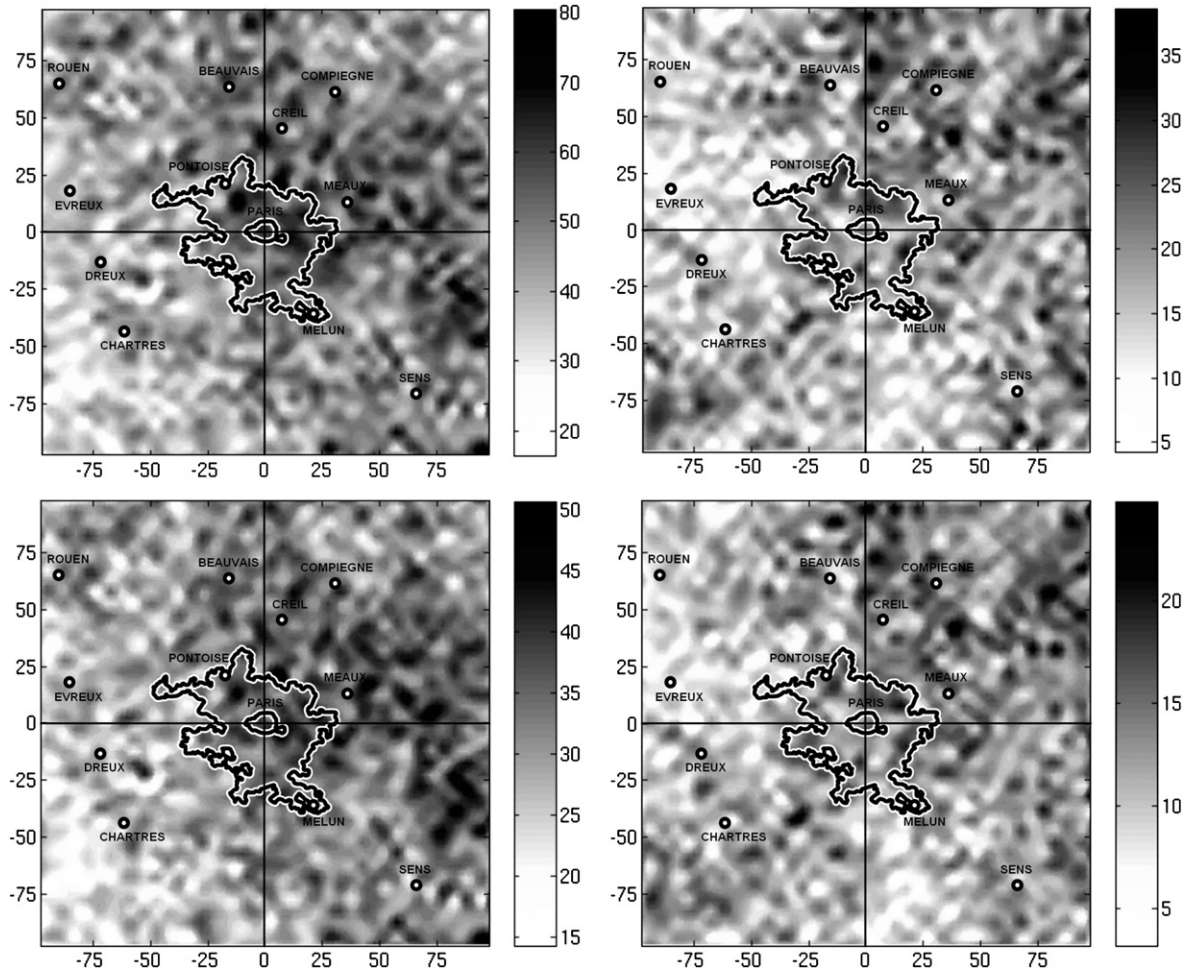
In an attempt to discriminate a possible effect of the pollutants from the influence of the UHI especially in the lee of Paris, we divided the data set into two subsets corresponding to week and weekend days. The UHI is assumed to remain constant whatever the day is, whereas the pollution should be reduced on weekends. This last hypothesis is supported by several observations performed by Airparif, a French organization that surveys the air quality in the region of Paris and the data of which are available on the website of the ADEME, the French agency for environment and energy management (<http://www.atmonet.org/>). For instance, the observations performed in an urban station (Paris, 18th district) from 1999 to 2003 show that pollutants like SO<sub>2</sub>, NO<sub>2</sub>, or PM<sub>10</sub> exhibit a decrease in concentration of about 20% during week-end days.

The discrimination between week and weekend days is presented in Fig. 12 where the total CG flashes during weeks (top left) and weekends (top right) and the total lightning days for weeks (bottom left) and weekends (bottom right) are displayed for filtered data with a maximum of 3 CG flashes per day and per pixel. One can point out that the total CG flashes and the total lightning days distributions are similar to each other for weekdays (Fig. 12, left), and also for weekend days (Fig. 12, right). This means that the CG flash density is closely correlated to the number of lightning days for filtered data. As far as week days are considered, their distributions are close to that of the overall period distributions since week days are the more numerous (467 week-days, i.e. 71% of the 657 lightning days). In this way, the general patterns are close to that issued from Fig. 7 (total lightning days) and 9 (total CG flashes).

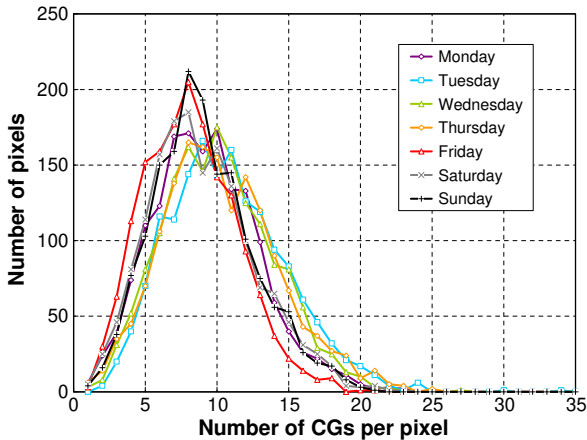
The main feature that arises from Fig. 12 is that the total CG flashes and the total lightning day distributions exhibit a relative maximum above and in the lee of Paris during week days (top left and bottom left in Fig. 12). When looking to the same distributions during weekend days (top right and bottom right in Fig. 12), one would expect about the same

behavior if pollution acts on lightning activity since pollution should be stronger above and in the lee of Paris also during weekend days. However, the pollution contrast between Paris and the other regions is not necessarily as strong during weekend days as during week days since the change in anthropogenic activity from week days to weekend days is probably more important in Paris and suburbs than in other regions. This could be an interpretation of the weak signal of pollution influence on lightning production above and in the lee of Paris in weekend days. The reduced data set for weekend days is also probably at the origin of this weak signal. For instance, 220,925 CG flashes (76% of the 290,780 CG flashes) were detected during 467 week days (71% of the 657 lightning days), and 69,855 CG flashes (24% of the 290,780 CG flashes) were detected during 190 weekend days (29% of the 657 lightning days). The filtering further reduces both actual data sets and especially the one of weekend days, but even with unfiltered data (not shown here) the vanishing of the main maximum above and in the lee of Paris is clearly discernible.

We also tried to find if a daily feature could be inferred from the CG lightning data. For that, we counted the number of CGs over 12 years in each pixel of the domain. Then we determined the occurrence frequency of CGs by bins of 2 events in each pixel (class n°1: between 0 and 2 CGs over 12 years; class n°2: between 2 and 4 CGs over 12 years; and so on...). It is then possible to display a histogram of the CGs occurrence by counting the number of corresponding pixels in each class bin. The calculation has been carried on for each day of the week; the results are displayed in Fig. 13. On average, the daily distributions have the same shape whatever the day is, with a maximum between about 7 and 10 CGs per 5  $\times$  5 km<sup>2</sup> pixels in 12 years (filtered data). However, one can clearly see that the distributions for Tuesday (green), Wednesday (red), and Thursday (yellow) are shifted toward larger class bins, i.e. toward higher numbers of CGs per pixel. On average, week days seem therefore more prone than weekend days to highest lightning activities. If it is supposed that pollution is at the origin of this daily behavior



**Fig. 12.** Total CG flashes per pixel (5 km  $\times$  5 km) over the whole period during May to September from 1992 to 2003 for weeks (top left) and weekends (top right) for a maximum number of flashes per day and per pixel equal to 3, and total lightning days per pixel over the whole period for weeks (bottom left) and weekends (bottom right).



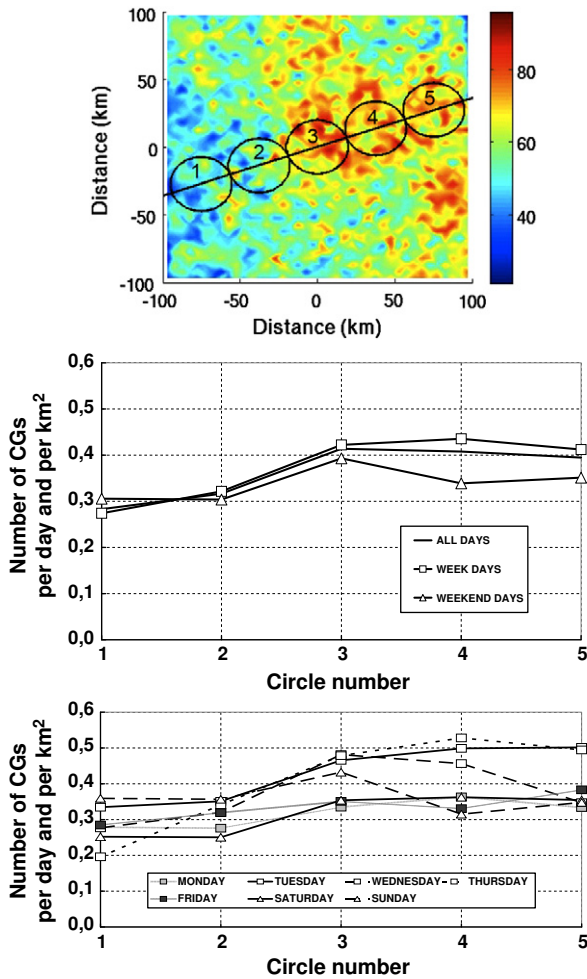
**Fig. 13.** Daily distributions of the number of pixels versus the number of CGs per pixel (2-CGs class bins) over the whole period during May to September from 1992 to 2003.

(the UHI is expected to remain unchanged), the results are in agreement with the aerosol hypothesis (Williams et al., 2002; Rosenfeld et al., 2008), according to which the presence of numerous CCN should enhance the electrification.

We did not perform further analysis of negative and positive CG flashes during week and weekend days because this study would have considered lower and lower numbers of CG flashes per day and per pixel that would be less and less meaningful.

## 6. Lightning distribution in the prevailing wind direction

In order to find if the polluted air mainly produced in the Paris area could have an impact on the lightning activity, we performed a daily count of CG lightning in 5 consecutive circles 20 km in radius along the axis of the prevailing wind through Paris city: 2 upwind, one over Paris, and 2 downwind (see Fig. 14). Given the Cartesian grid resolution and the size of the circles, each circle does not contain exactly the same number of pixels. Therefore we normalized the flash count by surface unity. The results are displayed in Fig. 14 for



**Fig. 14.** Top: definition of the five circles 20 km in radius in the prevailing wind direction through Paris. Middle: number of CGs per day and per km<sup>2</sup> in the five circles for all days together, week days, and weekend days. Bottom: number of CGs per day and per km<sup>2</sup> in the five circles for every day of the week.

all days, week days and weekend days (middle), and also for each of the days in a week (bottom).

Fig. 14 (middle) shows that the lightning activity markedly increases over Paris compared to upwind areas, then remains almost uniform for all days and for week days downwind of Paris, meanwhile it clearly decreases during weekend days downwind of Paris. Fig. 14 (bottom) provides a better insight of the daily variability of lightning activity along the prevailing wind axis. Although the signal is somewhat noisy because the samples are becoming smaller when splitting the data in 7 day sets, one unexpected feature arises when comparing all the curves. First of all, the lightning activity downwind of Paris (circles 4 and 5) appears relatively lower not only during weekend days but also on Monday and Friday. Secondly, on Wednesday the lightning activity remains relatively high in circle 4 but clearly decreases in circle 5, i.e. when the distance from Paris center exceeds about 50 km. At last, it's only Tuesday and Thursday that the lightning activity remains relatively high downwind

of Paris in the circle 5, that is to say beyond 50 km from Paris center. It seems that the lightning activity in the prevailing wind direction exhibits a weekly feature that does not match the usual week/weekend dichotomy.

## 7. Discussion

If the large event days are disregarded, the general feature of the CG lightning density over the considered domain exhibit maxima over Paris, and over the North, East, and South-East surrounding hills. At first sight, relief and UHI seem to be the most important ingredients in the enhancement of CG lightning activity in this area during the summer period. However, the East and North-East suburbs located in the lee of Paris are also substantially affected by CG lightning activity. Thus, the question on whether pollution may affect lightning in this area arises. Before addressing this question, we first focus on the influence of the relief and of the UHI in order to identify, as well as possible, their influence on the CG lightning distribution in the Paris area.

### 7.1. Influence of the relief

First of all, let us focus on the influence of the relief. On average – this is confirmed by the filtered data – there is a clear correspondence between the location of the highest hills of the domain and high CG lightning densities (over the North, East, and South-East surrounding hills). One could wonder why such a correspondence is not observed over the south-western hills of the domain. Is it because only the down slopes of these hills are present in the domain and only a residual CG lightning activity produced by upwind thunderstorms remains? Not shown here, an analysis at larger scale shows that significant CG lightning activity really appears only in the neighbouring of Paris under south-western fluxes. Therefore a deficit of lightning activity over these south-western hills probably originates from unfavorable conditions of atmospheric instability, surface characteristics, available water vapour... Further meteorological analysis is required to go further in the interpretation. Nevertheless, the correlation visible elsewhere confirms the observations of Pinto et al. (1999) who found a slight inclination for the flash tendency to increase with altitude.

A more detailed analysis allows studying further the influence of the relief where lightning activity is present. Except for the two very large events of 14 May 1998 and 26 July 2001, the higher the filtering threshold is, the higher the CG lightning activity seems to concentrate over several locations among which the hills around Beauvais and Sens, and the hills at the East of Meaux, are the most struck ones. The highest relief seems therefore to act as a multiplying factor of the CG lightning activity. As regards the main maximum in the North/North-East close suburbs of Paris, one can suppose that a wind convergence due to the small relief located between Pontoise and Maux, and the possible enhanced convergence at low level on the perimeter of the urban land cover (see Shem and Shepherd, 2009) could act together to reinforce locally the convection and consequently the electrification, producing high lightning events there. Actually, by means of numerical simulations of two convective thunderstorms Shem and Shepherd (2009) have shown

that the enhanced surface roughness in the urban land cover can induce a notable convergence ring at the urban–rural interface around the boundaries of the city. They suggested that urban morphology could play a key role in urban-induced convection via the roughness length, which would be consistent with the observations of the urban rainfall effect during the daytime when the UHI is not the highest. This enhanced convergence on the perimeter of the urban land cover could also be responsible from the secondary maxima over the West and South boundaries of Paris city when the largest thresholds are considered.

Bourscheidt et al. (2009) have recently shown that CG lightning density in South Brazil is correlated with the terrain slope and not the altitude. This feature seems also to appear in the Paris area, especially in the windward zones of the main ridge North-West to South-East directed between Rouen and Beauvais and of the secondary ridge, parallel to the main one, located tens of kilometers at the North of it and very close to Rouen (see Section 4). The same kind of behavior has been observed by De Souza et al. (2009) in South-Eastern Brazil, which is mostly affected by frontal systems coming from South. When reaching the mountains the convection is intensified and the CG lightning activity increases like the precipitation. After the mountains, the CG lightning activity is reduced and the intra-cloud discharges dominate.

Another feature that arises from the detailed analysis of the data is the high CG lightning activity in the Oise River valley, which passes by Pontoise, Creil, and Compiègne in the North of Paris. This characteristic clearly appears in Figs. 7 and 10 where the total lightning days per pixel and the total CG flashes per pixel (especially with a filtering threshold of 15 flashes per day and per pixel) are displayed, respectively. This means that lightning is often observed there and that the corresponding CG lightning activity is most often intense. This valley effect, which has been observed for many years (Triplet and Roche, 1986), is favored by the orientation of the valley that matches that of the dominant south-western winds and may also concentrate winds coming from close directions, resulting in a storm motion guiding. The feeding with the water vapour available in the valley ahead of the storm cells propagation is probably one of the most efficient processes that strengthen the convection and consequently the electrification. Could the accumulation of pollution along the valley have the same kind of impact? The question remains open without any aerosol observations available for this location.

In summary, altitude, slope and valley, are relief factors that seem to control a large amount of the general CG lightning flashes density in the Paris area during the warm season in connection with the wind direction.

## 7.2. Influence of the urban heat island

Besides the relief, the other process that could drive the intensification of lighting activity in the Paris area is the UHI (see Shepherd et al., 2002, for a review of the influence of the UHI on mesoscale circulations and resulting convection), which can reach up to 12 °C for a large city (Oke, 1987) and depends on several parameters. Steiger et al. (2002) and Naccarato et al. (2003) partly attributed the CG flash density

enhancement over Houston (Texas, USA) and over 3 large metropolitan areas in Brazil, respectively, to the influence of the UHI that is expected to reinforce convection. This mechanism could also be involved in the Paris region. When considering a South-West flux, i.e. the prevailing direction of the mid-troposphere winds, one can see a relatively sharp increase in the total number of lightning days per pixel (Fig. 7) close to Paris. This signal, also visible on the number of CGs per day from circle n°2 to circle n°3 in Fig. 14 (middle), could be partly attributed to the UHI on one hand, and to the pollution influence on the other hand (see Section 7.3). The influence of the UHI is probably more likely to act prior to the aerosols by triggering or reinforcing the convection when air mass is destabilized at its base by the warm surface conditions. Aerosols should act subsequently inside the clouds via the coalescence (see Section 7.3 for further discussion on this topic). But at this step, it is difficult to evaluate the real part played by each process in the increase in lightning activity from the southwest limits of Paris.

The UHI is in general more intense in summer and during the night with a maximum several hours after sunset and a minimum in the morning after sunrise (Pigeon et al., 2008). The UHI influence on convection is therefore expected to be more efficient from the afternoon until the early morning. However, its influence on the circulation is more observed during the daytime because of the urban–rural pressure gradient and the vertical mixing (see Shem and Shepherd, 2009). Present study does not bring any information on the time dependence of the convection in the urban environment. Further data analysis would be required to check if there is a possible time correlation between the UHI intensity and the lightning activity in order to better identify the possible influence of the UHI on the lightning distribution. Attention must be paid though to the hourly subdivision of the lightning data that could weaken their statistical meaning.

As far as the cover type is concerned, Shem and Shepherd (2009) have shown that the urban surface, characterized by a lower albedo, a higher sensible heat flux, and a lower latent heat flux due to the reduced moisture available and the lack of evapotranspiration, tends to modify the convection rather than to initiate it. Present observations are in agreement with this statement in the upwind side of Paris. As a matter of fact, the lightning activity is relatively weak in the South-West side of the city, and becomes strengthened over the urban area.

By using satellite's precipitation radar data from the Tropical Rainfall Measuring Mission (TRMM) Shepherd et al. (2002) have studied the rainfall modification by the UHI of great urban areas in the US for the warm season (1998–2000). They found that in comparison with upwind areas the rainfall rate moderately increases of about 6% over the metropolis. Furthermore they observed a clear tendency toward higher rainfall rates downwind of the cities (increase of about 28%) at a distance from the edge of the urban areas that stands within 20–60 km. Given that rainfall trends produced by deep convective storms often are similar to trends in ground flash rates (see MacGorman and Rust, 1998), one can expect that the influence of the UHI on the CG lightning density would be similar to that on the rainfall rate. As a matter of fact, Fig. 9 exhibits a maximum of the CG lightning activity over Paris

and more especially downwind of Paris within about 30 km from the edge of the urban area, which is in good agreement with the rainfall trends observed by Shepherd et al. (2002). The increase in the filtering threshold (see Fig. 10) seems to underline that the most active events would concentrate closer to Paris, and especially in the close North/North-East suburbs. Therefore, the supposed influence of the UHI on the CG lightning activity could be locally more efficient for large events in the close suburbs downwind of Paris.

One could wonder if the same process could be referred to explain the CG lightning pattern over Beauvais and Sens. However, the urban areas of both cities are far from equivalent to that of Paris since their diameters are smaller by a factor 10. Thus, it is highly doubtful that the CG lightning maxima over these cities may originate from their UHI influence. The specific topography of these two places could more probably induce wind convergence that could locally strengthen the convection.

### 7.3. Influence of the pollution

When looking to the CG density displayed in Fig. 9, one can clearly point out that the maximum of lightning activity deduced from filtered data is located over and in the lee of Paris according to the wind rose displayed in Fig. 4. For example, the total number of CG flashes per pixel over the whole period can exceed 90–100 above and in the lee of Paris meanwhile it amounts to only half of these values in the upwind region in the South-West of Paris. This result is in agreement with the observations reported by Naccarato et al. (2003) who detected the CG flashes over 3 great urban zones during 3 summers in Brazil. Their results exhibit an increase of about 60 to 100% of CG flashes on urban zones compared to surrounding rural zones. In the same way, Steiger et al. (2002) and Stallins et al. (2006) have observed an increase of about 45% of CG flashes on Houston from 1989 to 2000 and of about 50 to 75% on Atlanta from 1992 to 2003, respectively. Present result constitutes an apparent signal of the city influence on the lightning activity that probably originates from multiple causes. After having previously discussed several ones, let us now focus on the hypothesis that pollution may be responsible for a part of it.

Most of the convective clouds that arrive near Paris from the West/South-West may ingest low layer pollution before reaching the city since the feeding of the convective updraft is ensured near the ground ahead of the storm track. Given that the transport of the pollution inside the storm cell and its impact on the microphysical distribution and on the storm electrification must take time, it is expected that the strengthening of the lightning activity appears later, when the convective clouds are above the urban area. This is in agreement with the relative maximum of lightning activity that first appears above Paris in the upwind direction (Figs. 7 and 9). Since then, the thundercells should be continuously fed by urban aerosols until they have progressed too far in the lee side of the urban area. The influence of aerosols on the microphysical population and on the electrification process could continue on long distances depending on their clear-out by precipitation or on their transport rate in the spread ice phase of the anvil. As precipitation formation is expected to be delayed by the aerosols ingestion (Rosenfeld,

2000), those cells could remain in the atmosphere for a long time before decaying. This speculative scenario is consistent with the CG lightning activity observed here; the influence of pollution downwind of Paris would thus be sensitive over about one hundred of kilometers (see Fig. 9).

The influence of aerosols on cloud formation and precipitation has been the subject of several studies in the last decade in connection with the climate forcing question (Kaufman and Fraser, 1997; Ackerman et al., 2000; Koren et al., 2004; Rosenfeld et al., 2008). Some are related to convective clouds submitted to urban influence (Shepherd, 2005; Bell et al., 2008). In a review on the urban-induced rainfall Shepherd (2005) has pointed out the evidence that both UHI dynamics and aerosol-microphysics are key actors of the precipitation variability in urban environments. He has also come to the conclusion that “aerosols can have large impacts on the precipitation processes in clouds and can enhance or suppress precipitation depending on cloud type, seasonality, climate regime, or orographic profile of the urban area”. Therefore, the pollution produced by large urban areas is expected to influence the precipitation. This hypothesis is in agreement with the observations by Bell et al. (2008) who estimated from TRMM data that summertime rainfalls over the southeast U.S. are significantly higher during weeks than during weekends. They suggested that their observations were consistent with the aerosol theory according to which the ingested pollution suppresses cloud-drop coalescence allowing more water to be lifted above the 0° isotherm where it participates to the formation of iced hydrometeors and to the strengthening of the convection by releasing additional latent heat when freezing.

As a consequence of their influence on microphysics, aerosols are known to have an effect on the electrification of thunderstorms since they control the amount of supercooled water droplets that participate in the charging process in the mixed phase region (Rosenfeld and Lensky, 1998; Williams et al., 1999, 2002; Stallins et al., 2006; Saunders, 2008). But this effect is still difficult to evaluate all the more as additional aerosols beyond an optimum concentration can even decrease lightning activity (see Williams et al., 2002). Furthermore, the electrification of thunderstorms should also be sensitive to the Hallett–Mossop glaciation process that is supposed to provide high ice crystal concentrations favorable to the rate of particle collisions per unit volume (Hallett and Saunders, 1979).

On the basis of these studies and hypotheses, no firm conclusion could be drawn from present CG observations over Paris area. If the influence of pollution cannot be demonstrated and even less quantified, it can neither be rejected for the benefit of other potential causes like the relief or the UHI alone since, as a matter of fact, several signs are indicative of its impact on the CG lightning distribution. They are discussed hereafter.

First of all, if we look to the overall results on the domain and on the whole period (220,925 CG flashes during 467 week days; 69,855 CG flashes during 190 weekend days), the average number of CG flashes per day on the domain reaches about 473 during week days and only 368 during weekend days. This simple observation supports the aerosol hypothesis. As far as thermodynamic parameters are considered, some data provided by Météo France for summer

periods from 2001 to 2003 show that the average ground temperature measured in Paris exhibits a slight decrease from 18.75 °C down to 18.41 °C from Monday to Friday, and rises again 18.75 °C on Saturday and Sunday. Besides, everyday radiosoundings performed in Trappes (about 30 km of Paris in the west/southwest direction) during the same period show that the average relative humidity is faintly lower during weekend days than during week days by a small amount of about 1.5–2% between the 1000 and 700 hPa levels. Thus, weekend days seem slightly warmer and dryer than week days so that convection should not be significantly affected since both trends counteract. Moreover, the highest values of CAPE measured in the same period (ranging between 400 kJ kg<sup>-1</sup> and 1400 kJ kg<sup>-1</sup>) are roughly equally distributed among week and weekend days.

Secondly, the relative maximum lightning activity observed over and downwind Paris does not appear during weekends (see Fig. 12), when pollutants like SO<sub>2</sub>, NO<sub>2</sub>, or PM<sub>10</sub> exhibit a decrease in concentration of about 20%. This observation is of the same kind than that of Bell et al. (2008) for the precipitations in summer storms over the southeast United States. Given that the UHI is expected to remain unchanged from week to weekend (and of course the relief), this differential behavior is a good indicator of the pollution influence. Furthermore, when discriminating week and weekend days, the UHI influence becomes less obvious since the local maximum of CG flash density on the Paris area seems to disappear during weekends (Fig. 12). It would have been interesting to dispose of a hailpad network to verify if the mean hailstone size distribution would exhibit the same feature than that observed by Dessens et al. (2001). They found that this distribution shifted from small to large sizes between week days and weekend days, respectively, suggesting that lower anthropogenic emissions of ice-forming particles in the inland region surrounding Toulouse (southwest France) may be responsible for the hail change in weekends. One must remind though that weekend results are less meaningful because they represent only about 2/7 of the data set. As a matter of fact, localized differences in CG lightning density distinguishable in the southwest corner of the domain cannot be attributed to any pollution influence (Fig. 12, right).

Thirdly, the CG flashes distribution exhibits a relatively low activity of +CG in the northeast quarter and in the east of the domain, i.e. downwind Paris (Fig. 11, right) meanwhile the total lightning activity is the highest in this region. That is to say the percentage of positive CG is particularly low over and downwind Paris. It would have been interesting to perform the partition between week days and weekend days for this positive CG distribution but the data sets would have been really too small to provide any reliable information. Present result is in agreement with that of Stallins et al. (2006) who observed an area of reduced positive polarity flashes along a highway near Atlanta (Georgia, USA), and with that of Steiger et al. (2002) who detected a decrease of 12% of the percentage of positive flashes over Houston (Texas, USA). In both cases, Stallins et al. (2006) and Steiger et al. (2002) speculated that this pattern would be due to a change in thunderstorm's charge distribution because of pollution effects. Naccarato et al. (2003) have observed a decrease of 7–8% in the percentage of positive CG flashes over

three large metropolitan areas in Brazil. The same trend – a decrease of 7–19% in the percentage of positive CG flashes – has also been observed by Kar et al. (2009) over five major urban areas of South Korea. In both these last studies, a negative correlation has been pointed out between the PM<sub>10</sub> concentration and the percentage of positive flashes. Naccarato et al. (2003) postulated that this result could not be fully supported by the thermal hypothesis, giving evidence to the part played by the aerosol in the CG flashes polarity over urban areas (see Kar et al., 2009, for detailed explanations). Furthermore, the present results seem to agree well with the hypothesis by Jungwirth et al. (2005). By means of molecular dynamics simulations, they proposed a new charging mechanism at atomic scale to explain the nature of the charge transferred between colliding ice particles. They showed that when sulphate anions are less numerous as cloud condensation nuclei, the proposed charging mechanism predicts a shift toward positive charging of graupel. According to this hypothesis the less polluted days, i.e. weekend days, should exhibit higher +CG production, which is actually observed downwind of Paris.

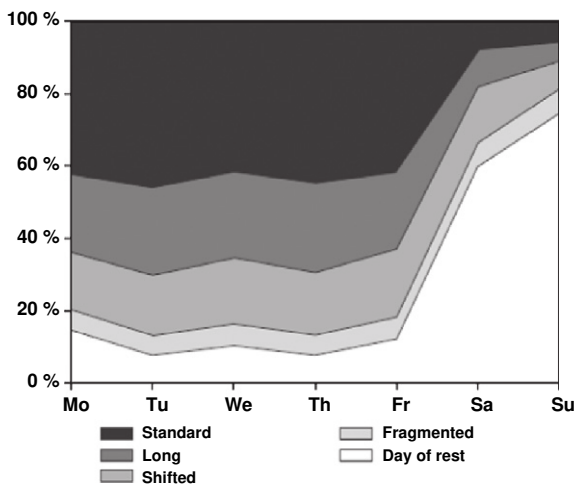
One can remind a discrepancy in the observations of positive CG production over urban area and during biomass burning events (Lyons et al., 1998; Murray et al., 2000; Lang and Rutledge, 2006). As a matter of fact, Lyons et al. (1998) and Murray et al. (2000) have reported a significant increase in the percentage of positive CG produced by thunderstorms contaminated by smoke from forest fires in southern Mexico that was advected into the U.S. southern and central plains in April–June 1998. Large concentrations of sulphate particle SO<sub>2</sub> would have a different impact on cloud microphysics than urban pollution (see Naccarato et al., 2003; and Kar et al., 2009). Smith et al. (2003) raised the question that a lack of moisture could be responsible for such a lightning anomaly in the lee of forest fires. Jayaratne et al. (1983) have experimentally found that impurities into water droplets (NaCl, NH<sub>4</sub> salts...) affect the charging produced by the non inductive mechanism meanwhile Avila et al. (1999) have shown that the cloud droplets spectrum, which is driven by aerosols, has an impact on graupel charge polarity in relation with the temperature.

The most striking result concerning the influence of pollution on the lightning activity is provided by the analysis performed along the axis of prevailing winds through the city of Paris. In a first step, the week days to weekend days differentiation shows that the lightning activity downwind of Paris appears relatively lower during weekend (Fig. 14, middle), reinforcing the hypothesis of the anthropogenic influence. Also detectable at the whole domain scale (Fig. 13), this tendency appears therefore significant. In a second step, the daily count in 5 circles aligned in the direction of prevailing winds suggests that the lightning activity remains relatively high downwind of Paris over a distance of about 90 km on Tuesday and Thursday, on a shorter distance on Wednesday (50 km), and remains low or decreases 20 km outside Paris (Fig. 14, bottom). The persistence of lightning activity in the wake of Paris could be considered as an indication of the influence of pollution. In fact, this behavior seems well correlated with the social activity in France. For instance, Lesnard and de Saint Pol (2008) studied the weekly rhythm of work in France using



data from a 1999 survey by INSEE (French National Institute of Statistics and Economic Studies). Fig. 15 adapted from Lesnard and de Saint Pol (2008) shows the percentage of each of the four types of work days: standard day, longer day, shifted day, fragmented day, and the percentage of rest day, and this for every day of the week. Tuesday and Thursday, and Wednesday to a lesser extent, are apparently the most worked days, likely to produce the strongest anthropogenic emissions. Even if no linear relationship can be deduced from the comparison of present results with the results of Lesnard and de Saint Pol (2008) – the difference between Tuesday and Thursday on one hand, and Monday and Friday on the other hand, is not so important compared to weekend days – one can legitimately question the signal deduced from lightning observation that puts forward the specific lightning activity during Tuesday and Thursday. At least, any further daily study should probably take into account the social activity of the considered country. For example, the week to weekend differentiation is probably not optimal.

Another hypothesis has not yet been put forward to account for lightning production associated with polluted events. Beyond the charging process controlled by the rate of particle collision, which depends on the microphysical population driven by the CCN concentration and by water contamination, one should discuss the lightning triggering conditions that have not been considered. Boussaton et al. (2007) have shown that the contamination of water with pollutants noticeably affects the characteristics of the corona discharges emitted by raindrops via a change in water conductivity. Tardiveau and Marode (2003) have experimentally shown that the presence of dielectric droplets is likely to modify the development of filamentary discharges by inducing a guiding effect and by reducing the critical potential for streamer-to-arc transition. According to Tardiveau and Marode (2003) the extraction of electrons from the droplets surface by photo-ionization (caused by hard photons produced in front of the streamer head by excited species) could further participate in the discharge process



**Fig. 15.** Distribution of types of days during a normal workweek of employed people (read: 15% of days on Monday are days of rest). Adapted from Lesnard and de Saint Pol (2008).

and favor its propagation. One could therefore expect some influence of the microphysics on the discharge propagation mainly during the branching phase of the leader (see Mazur, 2002). It is though too early to draw conclusions and further piece of work should be carried out on this topic to improve our knowledge of the involved mechanisms.

## 8. Summary and conclusions

Cloud-to-ground (CG) lightning flashes distribution over Paris area has been analyzed in terms of number of CG per day and per pixel and in terms of number of lightning days per pixel, for 12 summers from 1992 to 2003. Furthermore, we discriminated the week days and the weekend days lightning production on one hand, and we looked at the positive and negative CG flashes on the other hand. The main results can be summarized as follows:

- Specific large events must be disregarded in order to restore a statistical meaning to the whole data set. This is performed via the filtering of Gauthier et al. (2005). The distribution of CG flashes are comparable to the distribution of lightning days when lightning days whose flash counts exceed the 75th percentile of the cumulative distribution are disregarded in a given pixel.
- The CG flashes are statistically more numerous over and downwind Paris, giving evidence to an urban influence on the intensification of convection and CG lightning production. What are the parameters responsible for this influence? The possible part played by the relief, the UHI, and the pollution has been analyzed and discussed. A subdivision of the data set in function of the time (every hour) could reveal some correlation of the lightning activity with the intensity of the UHI and would therefore be interesting to perform.
- The data filtering is a good tool to determine the location of the increasingly hot spots. Those ones progressively concentrate over Paris and over some hills around, indicating that the UHI and the relief are undoubtedly involved in the most active events by strengthening the convection. The terrain slope seems to be a key parameter for identifying the influence of the relief, and a valley effect is pointed out in different locations. Further study taking into account the wind direction and the slope on each pixel could bring new insight in order to better identify the part played by the relief.
- The differentiation between week days and weekend days provides a good alternative for inferring the influence of pollution on CG lightning activity. Present results show that the maximum of CG flashes over and downwind Paris is markedly lessened during weekends. Given that the UHI is supposed to remain almost unchanged in average whatever the day is, this week-to-weekend differentiation tends to confirm the influence of pollution on the CG flashes production.
- The daily count of CG lightning in several circles along the axis of prevailing winds through Paris clearly shows a maximum of activity on Tuesday and Thursday (most worked days in France) downwind of Paris, over about 90 km. The lightning activity on Wednesday remains high on a shorter distance (50 km) and lower the other days.

– The additional discrimination between negative and positive CG flashes reveals that positive CG distribution does not exhibit any maximum over and downwind Paris as does the negative CG distribution, the positive CG percentage is therefore lower in these locations. This observation is in agreement with previous studies over urban areas in USA (Steiger et al., 2002; Stallins et al., 2006), Brazil (Naccarato et al., 2003), and South Korea (Kar et al., 2009), i.e. in various climatic zones, but also supports the new charging mechanism proposed by Jungwirth et al. (2005).

Present paper tends to bring some evidence on the influence of pollution on CG lightning activity over Paris area. It is known that aerosols have an impact on the microphysics and can further influence the degree of convection. More questions remain opened about the consequences of strong anthropogenic production on the charging processes and on the discharge triggering. We are far from quantifying the influence of pollution on thunderstorms. To do that, many parameters must be considered to account for the different observations reported. It remains a lot of uncertainties that will probably be solved with the help of powerful modelling that can address many processes from dynamics to lightning initiation, via aerosols influence on droplets spectra, on precipitation, on charging process; via pollution influence on charging process, and on discharge process.

According to the aerosol hypothesis (Williams et al., 2002; Rosenfeld et al., 2008), the presence of numerous CCN should enhance the electrification and reduce the efficiency of coalescence, thus act on precipitation formation. Therefore it would be interesting to compare lightning data to aerosol and precipitation observation in order to have a further insight in the aerosol signal on the lightning production. For instance, by carrying out similar methodology using TRMM observation (lightning with LIS and rainfall with microwave TMI), Lal and Pawar (2009) identified the difference in the aerosol influence on lightning signal during the premonsoon and monsoon seasons. To address this question on the Paris region during the past period studied here, the problem is collect extensive aerosol and precipitation data for the whole set of thunderstorm event. The focus on more recent years should be more adequate in order to benefit of the recent upgrades in the aerosol and precipitation observation.

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