Influence of the COVID-19 lockdown on lightning activity in the Po Valley

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Abstract

The relationship between aerosol concentration and lightning is complex. Aerosols can act as cloud condensation nuclei, contributing to the formation of cloud droplets, cloud electrification and lightning, while high concentrations of aerosols can contribute to a decrease in lightning due to radiative effects. Meteorology plays a dominant role in lightning activity, distorting the effect of aerosols. More measurements, as presented here, are needed to establish the complex relationship between aerosols and lightning.

The Po Valley, a heavily industrialized region, was highly affected by the COVID-19 lockdown. The reduction of non-essential activities and mobility coincided with a significant drop in pollutant concentrations and lightning. We investigate the relationship between lightning, meteorology and aerosols. We find that the variation in lightning during the lockdown cannot be fully attributed to meteorology. ~60% of the observed decrease can be attributed to meteorology, and ~40% to the reduction in aerosol emissions.

1 Introduction

Electrification of thunderstorms is produced by two different charging processes involving collisions between graupel and ice particles, i.e., non-inductive and inductive charging (Takahashi, 1978; Saunders, 1993). At a first stage, convection and gravity contributes to separate negatively charged graupel and positively charged ice near the cloud top (-30°C). At the second stage, graupel is accumulated at about the -10°C level and is combined with upward moving negative ice. Graupel is charged negatively below the -10°C level (Takahashi, 1978). Specific meteorological conditions can lead to the formation of inverted-polarity thunderstorms (Rust & MacGorman, 2002). For a more extensive description of charging processes, we refer to Takahashi (1978, 1984); Saunders (1993).

Thunderstorm electrification is highly influenced by dynamic and thermodynamic processes (Showalter, 1953). The meteorological conditions that lead to the formation of thunderstorms include (1) convergence, frontal activity or orographic lifting, (2) condensation at temperatures above freezing in convective clouds that extend to levels with temperature below freezing, (3) rising moist air reaching the level of free convection below the 500 hPa level, and (4) cooling aloft or warming with increasing moisture at low levels.

The non-linear influence of aerosols on lightning activity and precipitation has been investigated by several authors. Aerosols act as Cloud Condensation Nuclei (CNN) contributing to the formation of cloud drops and influencing the formation of raindrops (Tao et al. (2012) and references therein). High concentration of aerosols in the mixed-phase region contributes to the formation of small cloud droplets, causing a decrease in the rate of collision and coalescence of raindrops and delaying or suppressing precipitation (Nakajima et al., 2001; Tao et al., 2012). Some authors have reported an increase in lightning activity in areas with high concentration of aerosols, as in southeastern United States (Bell et al., 2008), in continental mixed-phase convective clouds (Williams & Stanfill, 2002) or downwind of metropolitan areas (Orville et al., 2001). Mansell and Ziegler (2013) studied the non-linear effect of CCN concentrations on the microphysical and electrical evolution of multicell storm using a numerical model. They reported an increase in graupel production with CCN concentration, leading to a higher rate of electrification and a high lightning activity. Lightning increases weakly with increasing CCN below 10^3 cm^{-3}, while for CCN between 10^3 cm^{-3} and 2×10^3 cm^{-3} lightning activity increases dramatically and then decreases for CCN > 2×10^3 cm^{-3}. High CNN concentrations produce droplets that are too small to initiate an efficient process of electrification (Takahashi, 1984; Mansell & Ziegler, 2013), .

The complex relationship between aerosols and lightning activity has been reported from several measurements. For example, Naccarato et al. (2003) reported a positive correlation between the number of Cloud-to-Ground (CG) flashes and the concentration of Particle Matter with 10 micrometers diameters and smaller (PM_{10}) particles together with a negative correlation between positive CG and the concentration of PM_{10} particles. Tan et al. (2016) reported the long-term effect of aerosols in lightning activity. According to Tan et al. (2016), high Aerosol Optical Depths (AOD) can contribute to a decrease of the lightning activity due to aerosol radiative effects. Thornton et al. (2017) reported an increase of lightning activity over major oceanic shipping lanes. L. Liu et al. (2020) reported that biomass burning aerosols contribute to invigorate cloud ice content, leading to a higher production of lightning. Shi et al. (2020) reported a positive correlation between AOD and lightning activity for AOD < 1 and a negative correlation for AOD > 1, while Sun et al. (2021) have reported an enhancement and a delay in the production of lightning activity in thunderstorms taking place under polluted conditions. Recently, Neto et al. (2020) have reported a decrease in the ratio of CG to Intra-Cloud (IC) lightning and in the lightning peak current of negative CG in Sao Paulo during the COVID-19 (coronavirus disease 2019) lockdown caused by the Severe Acute Respiratory Syndrome CoronaVirus 2 (SARS-CoV-2). Neto et al. (2020) have also reported an increase in the ratio of positive (+CG) to negative (-CG). These results suggest that aerosols could also play an important role for the characteristics of lightning flashes.

Some studies, such as Rosenfeld et al. (2014) or Wang et al. (2019) (and reference therein), have also reported a positive correlation between the Cloud Base Height (CBH) of thunderstorms with a high concentration of aerosols and the concentration of aerosol particles. L. Liu et al. (2020) have reported a complex relationship between biomass burning aerosols and CBH. They have reported contrasting responses affected by the cloud water content between different vertical layers.

The Po Valley in northern Italy is an elongated west-east orientated plain basin with a high lightning activity due to different factors, such as the proximity to mountains, the moisture flux from the Adriatic sea and the convergence of cold and warm air masses from the North and the South, respectively (Feudale et al., 2013; Feudale & Manzato, 2014; Anderson & Klugmann, 2014). The Po Valley is also an area highly affected by aerosols emitted from large urban areas and emissions from industrial zones, road, shipping and air traffic (Squizzato et al., 2013). Especially northern Italy was significantly affected by the COVID-19 pandemic, leading to a dramatic reduction in the industrial activity and traffic during the COVID-19 lockdown declared by the Italian government between March 9th and May 18th 2020 (Cameletti, 2020) and followed by a long period of de-escalation of the lockdown measures in which there were some important mobility restrictions that lasted until summer 2020 (Lolli et al., 2020). The COVID-19 lockdown coincided with a significant drop in the concentration of air pollutants, including Particle Matter with 2.5 micrometers diameters and smaller ($PM_{2.5}$) (Lolli et al., 2020; Zoran et al., 2020; Mertens et al., 2021; Jones et al., 2021). In this work, we study the reduction in the emission of $PM_{2.5}$ particles in the Po Valley during the COVID-19 lockdown and for the first time its influence on thunderstorm characteristics (e.g. CBH) and their lightning activity.

2 Data

2.1 Lightning data

We use lightning data provided by the Lightning Locations System Earth Network Total Lightning Network (ENTLN) C. Liu and Heckman (2011); Zhu et al. (2017); Lapierre et al. (2020) over the Po Valley (between 7°E and 12°E longitude degrees and 44°N and 46°N latitude degrees) between January 2017 and December 2020. ENTLN is composed by globally distributed Very Low Frequency (VLF) sensors that provide the position, time of occurrence, polarity and peak current of lightning strokes. In this work, we use the flash product provided by ENTLN.

Lightning data from the space-based instrument Lightning Imaging Sensor (LIS) R. J. Blakeslee et al. (2014); R. Blakeslee et al. (2020) onboard the International Space Station (ISS) is used to estimate the Detection Efficiency (DE) of ENTLN over the Po Valley between 2017 and

2020. ISS-LIS detects optical emissions from lightning with a frame integration time of 1.79 ms (Bitzer & Christian, 2015) with a spatial resolution of 4 km (R. Blakeslee et al., 2020), covering latitudes between 54.3°N and 54.3°S (R. Blakeslee et al., 2020). The total DE of ISS-LIS ranges between 51 and 75% (R. Blakeslee et al., 2020).

ENTLN has a DE of about 90% for CG strokes over the U.S. (Zhu et al., 2017; Lapierre et al., 2020) and a total global stroke DE of about 57% (Bitzer et al., 2016). We use the ISS-LIS lightning flash data together with the Bayesian technique proposed by Bitzer et al. (2016) to estimate the total flash (CG+IC) DE of ENTLN over the Po Valley between 2017 and 2020. For the years 2017-2020 we find a DE of 0.77 / 0.66 / 0.92 / 0.78, respectively, based of 16 / 20 / 21 / 15 thunderstorms. Therefore, we assume that the total flash DE of ENTLN has not changed significantly between 2017 and 2020, so that we can compare the total number of lightning flashes reported by ENTLN within this time frame.

2.2 Aerosol data

We use air quality information provided by the European Environment Agency (EEA) (Schleidt, 2013). This database consists of a multi-annual time series of air quality measurement data and calculated statistics for a number of air pollutants. In particular, we use the concentrations of $PM_{2.5}$ particles reported between 2017 and 2020 by ground-based stations covering the whole west-east extension of the Po Valley located in the cities of Brescia (stations 26183 and 35230), Cremona (stations 25794 and 26178), Milan (stations 26080, 26417, 26398, 24744 and 62002), Pavia (station 25510), Turin (stations 24177, 24588, 26261 and 64840) and Treviso (station 25398). When more than one station provides the concentration of $PM_{2.5}$ during one day in one city, we take the average concentration over all the stations located in the same city as the daily value. Following this approach, we find 1412 days with measurements in Brescia, 1414 in Cremona, 1416 in Milan, 1249 in Pavia, 1196 in Turin and 1191 in Treviso (out of 1461 days). Therefore, days without measurements are rare and rather homogeneously distributed over the period between 2017 and 2020, except for in Treviso, where there are no measurements between July and September 2020. Finally, we calculate the daily concentration of $PM_{2.5}$ over the Po Valley as the average over all the cities with measurements.

2.3 Meteorological data

The COVID-19 lockdown contributed to a strong reduction in air pollutant emissions in several regions of the world (Shi et al., 2021). However, decreases in $PM_{2.5}$ concentrations and other air pollutants during the COVID-19 lockdown are not only influenced by the reduction in emissions. According to Shi et al. (2021), changes in meteorology that are not directly connected to the COVID-19 lockdown significantly contributed to the reduction in air pollutants over several cities, including Milan. Therefore, meteorological conditions during the COVID-19 lockdown period in the Po Valley have to be taken into account to isolate the effect of aerosols on lightning activity. We analyze the meteorology between 2017 and 2020 over the Po Valley using meteorological data from the European Centre for Medium-Range Weather Forecasts (ECMWF) fifth generation reanalysis (ERA5) (Hersbach et al., 2020). Among other products, ERA5 provides 1-hourly, daily and monthly meteorological data using a 4D-var assimilation scheme at 139 pressure levels with an horizontal resolution of 0.25°. We analyze monthly averaged data of the Boundary Layer Height (BLH), total precipitation, relative humidity at surface and at 850 hPa pressure level, temperature difference between 850 hPa and 300 hPa pressure levels, temperature at surface and CBH. These variables will serve to establish the meteorological conditions for deep convection during the lockdown and their possible impact on lightning activity. We also analyze the geopotential height at 500 mb level between 2017 and 2020 over Europe (see the Figures S6 and S7 in the supporting material) from images provided by the NOAA/ESRL Physical Sciences Laboratory Kalnay et al. (1996).

In addition, we analyzed the 1-hourly ERA5 Cloud Base Height (CBH) data for all the lightning flashes reported by ENTLN in the Po Valley for the period 2017-2020 in order to investigate the possible relationship between the concentration of aerosols and the CBH in thunderclouds.

Finally, we use the Cloud Top Height (CTH) product provided by EUMETSAT to estimate the role of CTH in lightning activity (Price & Rind, 1992). The CTH product provided by EUMETSAT is based on measurements of the Meteosat Second Generation (MSG) satellites. The geostationary orbit of MSG satellites is centered at 0°E, 0°N, reporting data at the rate of one Earth full-disk scan every 15 min (Schmetz et al., 2002). The CTH product is calculated by EUMETSAT from data acquired by the Spinning Enhanced Visible and InfraRed Imager (SEVIRI) instrument onboard the MSG satellites with an horizontal resolution of 4 km at the center of the orbit and a vertical resolution of 320 m, reaching a maximum altitude of 16 km. In this work, we collect 4-hourly CTH values over the Po Valley between March and October and between 2017 and 2020.

3 Analysis and results

In this section, we combine the lightning data, the concentration of $PM_{2.5}$ with the meteorological conditions during the COVID-19 lockdown period in the Po Valley to determine how these factors impacted the lightning activity.

Figure 1(a) shows the monthly concentration of $PM_{2.5}$ during days with thunderstorms (definition: at least one lightning flash reported by ENTLN in the region) between 2017 and 2020 as the mean value measured in Brescia, Cremona, Milan, Pavia, Turin and Treviso. We do not include November 2020 in this analysis, as there were not any thunderstorm in the region according to ENTLN lightning data. The mean value of the concentration of $PM_{2.5}$ was lower in April and June 2020 than in previous years, due to the reduction of emissions during the COVID-19 lockdown. In May 2020, the concentration of $PM_{2.5}$ was similar as in 2019, but lower than in May 2018 and May 2017. The concentration of $PM_{2.5}$ particles during the period between July and September 2020 was closer to the climatological median than in previous months. Finally, the concentration of $PM_{2.5}$ was significantly lower than in previous years in October and December 2020, possibly due to new restrictions and a reduction in mobility.

Table 1 collects $PM_{2.5}$ concentration, lightning, and CBH data for thunderstorm days between March and June 2017-2020. Second and third columns clearly show a dramatic reduction in the total number of flashes between March and June 2020 with respect to the climatological mean in coincidence with a slight reduction in the concentration of $PM_{2.5}$ particles, as we will discuss in Fig. 2. The average total number of flashes during March, April, May and June (2017-2019) are 4928 / 39388 / 356749 / 265783, while during the same months in 2020 the total number of flashes are 529 / 4280 / 29721 / 128618. Therefore, there was a reduction of about 1 order of magnitude in the total number of flashes during the COVID-19 lockdown and the following de-escalation period over the Po Valley (March-June 2020). The total number of days with thunderstorms were particularly low during April 2020 (8 days, while the climatological mean is 16). The ratio of IC to CG flashes between March and June 2020 was slightly higher than the climatological mean. Finally, the last column suggests lower-based thunderclouds between April and June 2020 with respect to average of previous years (about 10% lower).

Figure 1(b) shows the monthly data of the total lightning flashes normalized by the monthly total number of days with thunderstorms over the Po Valley between January and December in 2017, 2018, 2019 and 2020. This figure clearly shows a dramatic reduction in the total number of flashes per thunderstorm during the COVID-19 lockdown and de-escalation period (March to June 2020) with respect to previous years. Lightning activity after the lockdown is slightly higher than the climatological mean (July and August 2020), dropping again in September and October 2020 when COVID-19 increased again. Finally, lightning activity is higher than the climatological mean again in December 2020. Lightning activity is low in January, February and December. Therefore, variations with respect to the climatological means in January, Febru-

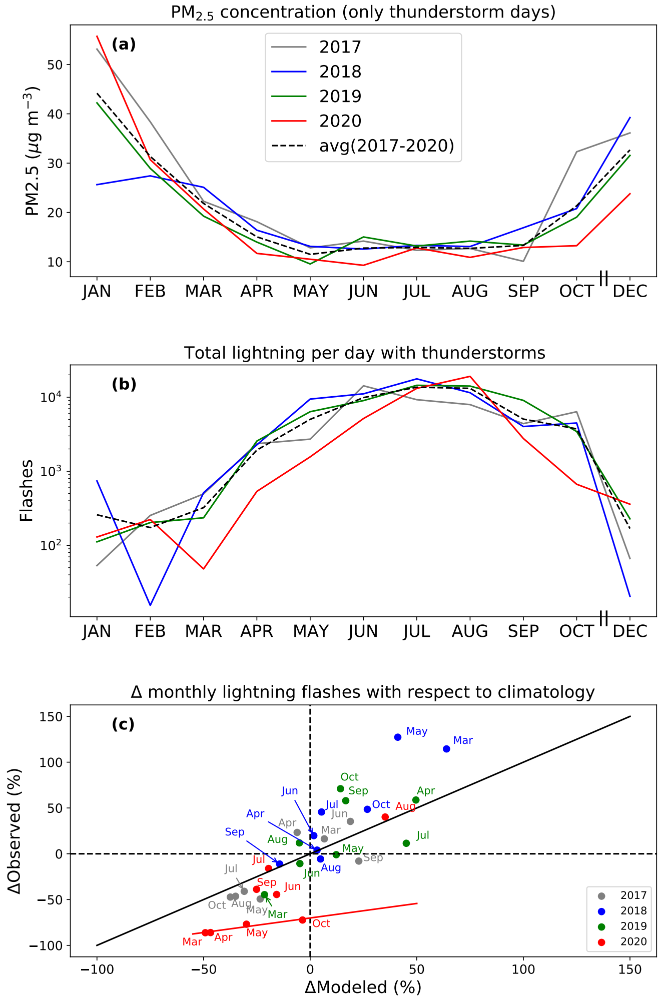

Figure 1. Panel (a-b): Monthly average of (a) the concentration of $PM_{2.5}$ during days with thunderstorms averaged over all the stations in the selected Po Valley and (b) the total lightning flashes for days with thunderstorms between January and December in 2017, 2018, 2019 and 2020. November is not included because ENTLN did not report any thunderstorm in the Po Valley in November 2020. Dashed lines correspond to the monthly climatological mean between 2017 and 2020. Panel (c): Monthly observed and modeled variations of lightning activity between March and October between 2017 and 2020. The modeled variations have been obtained as the average of the monthly variation predicted by the lightning parameterizations by Price and Rind (1992); Romps et al. (2014) and Finney et al. (2014). The solid black line corresponds to the limit at which observed and modeled monthly variations of lightning activity would be in agreement. March, April, May and October 2020 values have been fitted to a line (red line).

Table 1. Monthly mean concentration of $PM_{2.5}$ during days with thunderstorms, total number of lightning flashes, total number of days with thunderstorms, IC/CG ratio and CBH in thunderstorms.

Month	Averaged $PM_{2.5}$ during days with thunderstorms	Lightning flashes	Days with thunderstorms	IC/CG	CBH (m)
March 2017	22.26	4453	9	1.94	498
March 2018	25.10	8211	16	0.71	349
March 2019	19.25	2120	9	0.91	1066
March 2020	20.70	529	11	1.37	1150
April 2017	18.12	37740	16	3.94	1165
April 2018	16.40	31839	14	1.58	556
April 2019	13.98	48586	19	0.79	848
April 2020	11.69	4280	8	1.45	978
May 2017	12.83	650750	24	3.90	1121
May 2018	13.12	292202	31	2.79	980
May 2019	9.55	127296	20	1.50	637
May 2020	10.51	29721	19	1.73	853
June 2017	14.18	313252	22	3.63	1043
June 2018	12.57	277317	25	2.97	1020
June 2019	15.03	206780	23	3.92	1297
June 2020	9.28	128618	25	2.23	793
March-June 2017-2020	15.29	135231	18	2.21	897

ary and December are not as reliable as in summer. Fig. 1S in the supplementary material shows the temporal evolution of the ratio of IC to CG and the ratio of +CG to -CG lightning flashes.

The reported decrease in the lightning activity by thunderstorm days during March, April, May, June, September and October 2020 can be influenced by the reported decrease in the concentration of $PM_{2.5}$ (Figure 1(a)) and/or by meteorology (see Fig. S2-S7 in the supplementary material). We can use lightning parameterizations based on meteorological variables as proxy for lightning in order to isolate the effect of aerosols in lightning activity. In this work, we use the following lightning parameterizations for the time period March-October 2017-2020:

1. Price and Rind (1992) developed a parameterization based on CTH. This parameterization produces good lightning estimates over the Po Valley (Gordillo-Vázquez et al., 2019). We have used the CTH product provided by EUMETSAT every 4 hours over the Po Valley to estimate the monthly change in lightning activity with respect to the climatological mean (2017-2020) in the Po Valley between March and October between 2017 and 2020 following the parameterization by Price and Rind (1992).
2. Romps et al. (2014) developed a parameterization that uses the product CAPE × Precipitation (CAPE × P, or CPCAPE) as a proxy for lightning. This parameterization produces good lightning estimates over land (Romps et al., 2018; Gordillo-Vázquez et al., 2019). We have used the monthly averaged CAPE × P product from ERA5 following the parameterization by Romps et al. (2014).
3. The lightning parameterization developed by Finney et al. (2014) (ICEFLUX) uses the flux of ice at 440 hPa pressure level to estimate the lightning flash density. We have used the hourly averaged vertical velocity, content of ice and cloud cover at 450 hPa level from ERA5 following the parameterization by Finney et al. (2014).

We show in Figure 1(c) the monthly observed and modeled deviation of the climatological mean of lightning activity between March and October between 2017 and 2020 as colored dots. The modeled variations have been obtained as the average of the monthly variation predicted by the three previously described lightning parameterizations (Price & Rind, 1992), Romps et al. (2014); Finney et al. (2014). According to our results, the lightning parameterizations based on the CTH, the CAPE × P product and the flux of ice at 450 hPa level are not enough to explain the observed decrease in lightning activity in 2020 during March, April, May, June, September and October, suggesting an additional influence by aerosols (here $PM_{2.5}$ concentration). We have calculated the Pearson's correlation coefficient for both variables (monthly observed and modeled variations of lightning activity), obtaining 0.69 for the entire period and 0.72 for the period between 2017 and 2019. The better performance of lightning activity between 2017 and 2019 with respect to 2020 also suggests an additional influence of the $PM_{2.5}$ concentration on lightning activity. It is interesting to note that the points corresponding to March, April, May and October 2020 are especially far from the line at which observed and modeled monthly variations of lightning activity would be in agreement (slope = 1) and are also some of the months when $PM_{2.5}$ concentration was distinctly lower than the climatological mean. We have fitted these points to a line (red line in Figure 1(c)), obtaining a slope of 0.2. The deviation of these points with respect to the black line suggests that the low values of $PM_{2.5}$ concentration played an important role in the reduction of lightning activity. In June 2020, the concentration of $PM_{2.5}$ was also distinctly lower than the climatological mean. However, the point representing June 2020 is closer to black line, which suggests that meteorology played a more important role in the reduction of lightning activity than in March, April, May and October 2020.

The monthly averaged deviation between modeled and observed lightning activity between March and October 2020 is -36%. We can then propose the hypothesis that the decrease in $PM_{2.5}$ emissions during 2020 contributed to the 36% of the decrease in lightning activity, while the lightning parameterizations based on meteorology can only explain the 64% of the observed decrease. In particular, we have found that the CTH-based, the CPCAPE and the ICEFLUX parameterizations can only explain the 64%, the 77% and the 51% of the observed decrease in lightning, respectively.

Let us now check this hypothesis by analyzing the relationship between the concentration of $PM_{2.5}$ and lightning activity for each individual thunderstorm day. Figure 2(a) shows the total flashes per day in between 2017 and 2020 versus the daily concentration of $PM_{2.5}$ for all the days with thunderstorms over the Po Valley. Thunderstorms taking place in 2020 (red dots) had a lower concentration of $PM_{2.5}$ particles and produced a lower total number of lightning flashes than thunderstorms taking place in April 2017, 2018 and 2019. We have fitted these data with a Gaussian distribution, obtaining that the peak is reached at 12 μg m^{-3} and a standard deviation 6×10^{-6}. This result suggests that lightning activity tends to increase with the concentration of $PM_{2.5}$ for concentrations below 12 μg m^{-3} and decreases for higher concentrations above this threshold. This result is in agreement with previous studies of the influence of aerosols concentration in lightning (Naccarato et al., 2003; Tan et al., 2016; Shi et al., 2020).

We have calculated the Pearson's correlation coefficient for these variables (Figure 2), finding a positive correlation between the concentrations of $PM_{2.5}$ and daily lightning activity (r=0.116) with $p-value$=0.032 (that is lower than the commonly used threshold 0.05) for concentrations of $PM_{2.5}$ below 12 μg m^{-3} (Fig. 2(a)). For concentrations of $PM_{2.5}$ larger than 12 μg m^{-3}, we have obtained a negative correlation between (r=-0.195) with a $p-value$ lower than 0.05.

Figure 2(b) shows the ratio of IC to CG lightning flashes versus the concentration of $PM_{2.5}$ particles in April 2017-2020. As in the previous case, we have fitted the data to a Gaussian distribution to obtain the peak (15 μg m^{-3}) and the standard deviation (0.8). We have calculated the Pearson's correlation coefficient for these variables, finding a positive correlation between them (r=0.224) with a $p-value$ lower than 0.05 for concentration of $PM_{2.5}$ lower than 15 μg m^{-3} and a negative correlation (r=-0.289) with a $p - value$ lower than 0.05 for concentration of $PM_{2.5}$ larger than 15 μg m^{-3}. According to these results, aerosols could play an important role in the ratio of IC to CG.

We plot in Figure 2(c) the CBH value versus the concentration of $PM_{2.5}$ for days with thunderstorms in April 2017-2020. We obtain the peak of the Gaussian fit in 17 μg m^{-3} and a standard deviation 2×10^{-4}. We find a positive correlation between both variables (r=0.157) with a $p-value$ lower than 0.05 for concentration of $PM_{2.5}$ lower than 17 μg m^{-3} and a neg-

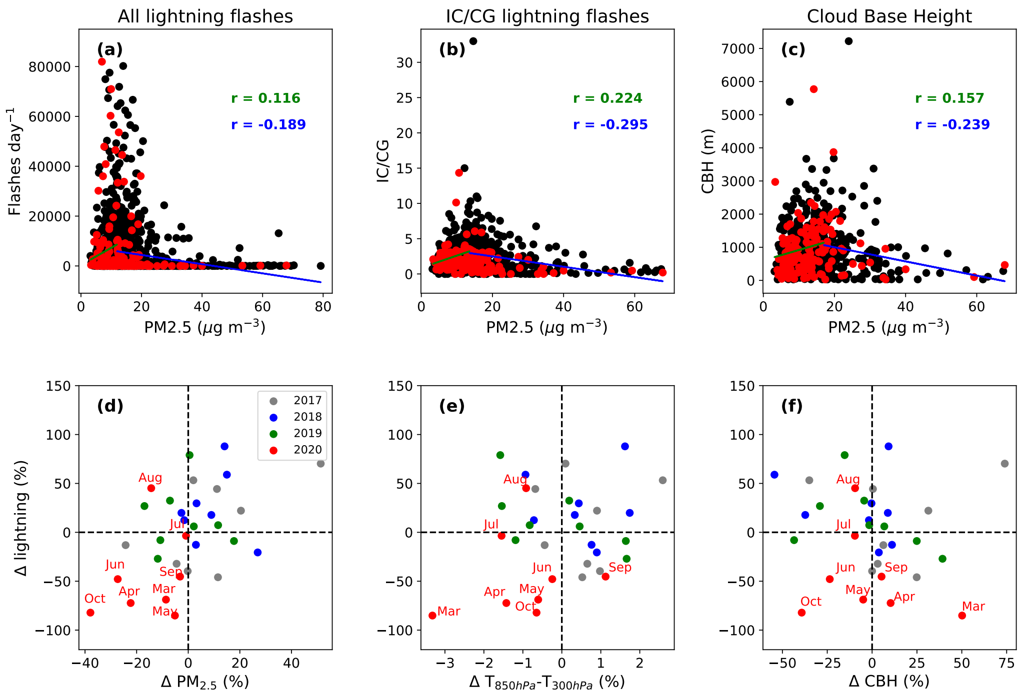

Figure 2. Scatter plots of the (a) total number of flashes per day, (b) ratio of IC to CG lightning flashes and (c) CBH in thunderstorms versus the concentration of $PM_{2.5}$ particles for days with thunderstorms for 2017-2019 (black dots) and 2020 (red dots). We have fitted the data as explained in the text and show the Pearson's correlation coefficients r before (green) and after (blue) the peak and the $p - value$ for each fitting. We show the fitting lines before (green) and after (blue) the peak. The panels (d-f) show the deviation of lightning per thunderstorm days with respect to the climatological mean on a monthly basis versus the deviation of some meteorological variables with respect to the climatology on a monthly basis.

ative correlation (r=-0.262) with a $p{-}value$ lower than 0.05 for concentration of $PM_{2.5}$ larger than 17 µg m^{-3}. These results suggests a complex relationship between the CBH and the concentration of aerosols, reported by previous studies (Rosenfeld et al., 2014; Wang et al., 2019; L. Liu et al., 2020).

Finally, Figures 2(d-f) show the monthly deviation between March and October of lightning per thunderstorms days with respect to the climatological mean versus the monthly deviation of some meteorological variables with respect to the climatology, such as the concentration of $PM_{2.5}$ particles during thunderstorm days, the temperature difference between the 850 hPa and the 300 hPa pressure level and the CBH. We show in Figure S5 in the supporting materials a similar analysis of the BLH, the total precipitation and the RH at 850 hPa. We have labeled all months of 2020. Figures 2(d-f) indicate that March, April, May, June, September and October 2020 were characterized by a pronounced reduction of lightning activity and $PM_{2.5}$ particle concentration with respect to the climatological mean and by a trend to low temperature differences between 850 hPa and 450 hPa pressure levels.

4 Discussion

The unprecedented COVID-19 lockdown during March 9th and May 18th 2020 and subsequent de-escalation period in the heavily industrialized area of the Po Valley have enabled us to investigate the effects of a reduction in the concentration of aerosols in lightning activity.

We compared the climatology of lightning during 2020 with previous years (Figure 1). According to our results, a pronounced reduction in lightning activity between March and June 2020 coincides with a reduction in the concentration of $PM_{2.5}$ during the lockdown and de-escalation periods (Figure 1(a, b)) and cannot be fully attributed to meteorology (Figure 1(c)). We have used three lightning parameterizations based on meteorology to estimate the effect of the reduction of $PM_{2.5}$ concentration on lightning activity. We have found that ~64% of the observed decrease can be attributed to meteorology using the three parameterizations, and ~36% to the reduction in aerosol emissions.

The scatter plot in Figure 2(a) suggests an increase in lightning activity for increasing $PM_{2.5}$ concentrations up to nearly 12 μg m^{-3}, followed by a decrease in lightning activity with increasing $PM_{2.5}$ concentrations beyond 12 μg m^{-3}. Our results suggest that anthropogenic aerosols emitted in the Po Valley influence the mixed-phase region of thunderstorms where electrification occurs, playing an important role in the cloud charge layer structure and in the occurrence of lightning. These results are in agreement with previous observations [e.g., Orville et al. (2001); Williams and Stanfill (2002); Bell et al. (2008)] and modeling results (Mansell & Ziegler, 2013) that reported a positive correlation between the concentration of aerosols and lightning activity for low and moderate concentration of aerosols, together with a negative correlation for high concentrations of aerosols. Different type of aerosols measurements employed by Orville et al. (2001); Williams and Stanfill (2002); Bell et al. (2008); Mansell and Ziegler (2013) and this work prevents direct comparison between the threshold value at 12 μg m^{-3} $PM_{2.5}$ concentration.

We have found a possible linear correlation between the ratio of IC to CG lightning and the concentration of $PM_{2.5}$ (see Figure 2(b)). As we discussed in the Introduction, aerosols play an important role in cloud electrification. The found possible relationship between the concentration of $PM_{2.5}$ particles and the ratio of IC to CG suggests that the role of aerosols in cloud electrification could also influence the structure of charges in thunderclouds, affecting differently the occurrence of each type of lightning flashes.

Aerosols in the mixed-phase region play a significant role in the formation of cloud droplets and raindrops Tao et al. (2012). Therefore, aerosols could play a role for the CBH. Some studies (Rosenfeld et al., 2014; Wang et al., 2019) have reported a positive correlation between CBHand a high concentration of aerosols. According to our results, the CBH in thunderstorms can be linearly correlated with the concentration of $PM_{2.5}$ (see Figure 2(c)). However, a deeper investigation of this possible relationship is out of the scope of this work.

The effect of aerosols on lightning activity can be masked by meteorological conditions. However, Figure 1(c) and Figures 2(a-c) suggest that aerosols could play a significant complex role in the formation of clouds and in thunderstorm electrification that can be distinguish from the role of meteorology. Identifying the role of aerosols can be useful to improve lightning parameterizations, as suggested by the parameterization developed by Stolz et al. (2017) that uses the CCN concentration in the boundary layer as a proxy for lightning activity. Understanding the role of aerosols in lightnign activity over the Mediterranean basin can also serve to better forecast lightning-ignited wildfires (Pérez-Invernón et al., 2021)

5 Summary and conclusions

The main conclusions of this work are:

1. The COVID-19 lockdown and the following period of de-escalation coincided with a dramatic reduction in lightning activity of 70% and in the concentration of $PM_{2.5}$ in thunderstorm days of 15% over the Po Valley in Italy.
2. The reported decrease in lightning activity cannot be fully attributed to meteorology, here represented by the vertical profiles of the temperature and the RH, the total precipitation, the BLH, the geopotential height, the CTH, the product CAPE × Precipitation and the flux of ice at 450 hPa.
3. We have found a positive correlation between lightning activity in the Po Valley and the concentration of $PM_{2.5}$ particles for low and moderate concentrations (<12 μg m^{-3}) together with a negative correlation for higher concentration of $PM_{2.5}$ (>12 μg m^{-3}), which might explain the observations stated in (1.).
4. Furthermore, our results suggest a positive correlation between the concentration of $PM_{2.5}$ particles and the ratio of IC to CG lightning and between CBH, respectively, for low and moderate concentrations of $PM_{2.5}$. We have also found a negative correlation between these variables for higher $PM_{2.5}$ concentrations.

Our results are based on a relatively short time interval. However, the reported correlations between lightning activity, CBH and the concentration of $PM_{2.5}$ over the Po Valley are statistically significant. These results suggest that anthropogenic aerosols could play an important role for the lightning activity over the Po Valley, as also suggested by the investigation of the impact of the COVID-19 lockdown on lightning activity over Brazil by Neto et al. (2020).

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