Atmospheric Research 263 (2021) 105808

Contents lists available at ScienceDirect

Atmospheric Research

journal homepage: www.elsevier.com/locate/atmosres

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

F.J. Pérez-Invernón [a,*], Heidi Huntrieser [a], F.J. Gordillo-Vázquez [b], Sergio Soler [b]

[a] Deutsches Zentrum für Luft- und Raumfahrt, Institut für Physik der Atmosphäre, Oberpfaffenhofen, Germany
[b] Instituto de Astrofísica de Andalucía, Glorieta de la Astronomía s/n, 18008 Granada, Spain

ARTICLE INFO

Keywords:
Lightning
Aerosols
COVID-19
Could base height
Atmospheric electricity
Pollutants

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 as compared to recent years cannot be fully attributed to meteorology. ~60 ± 10% of the observed decrease is attributed to meteorology, and ~40 ± 10% 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. At the second stage, graupel is accumulated at about the $-10\,^{\circ}$C level and is combined with upward moving negative ice. Graupel is charged negatively below the $-10\,^{\circ}$C level (Takahashi, 1978). Specific meteorological conditions can lead to the formation of inverted-polarity thunderstorms (Rust and 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; Tsenova et al., 2016; Saunders, 2017; Dye and Bansemer, 2019). 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, contributing to the downdraft of cold air and maintaining air motion.

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 and 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 $10^3\,\mathrm{cm}^{-3}$, while for CCN between $10^3\,\mathrm{cm}^{-3}$ and $2\times10^3\,\mathrm{cm}^{-3}$ lightning activity increases dramatically and then decreases for CCN $>2\times10^3\,\mathrm{cm}^{-3}$. High CNN concentrations produce droplets that are too small to initiate an efficient process of electrification (Takahashi, 1984; Mansell and Ziegler, 2013).

The complex relationship between aerosols and lightning activity has

---

* Corresponding author.
E-mail address: FranciscoJavier.Perez-Invernon@dlr.de (F.J. Pérez-Invernón).

https://doi.org/10.1016/j.atmosres.2021.105808
Received 9 June 2021; Received in revised form 28 July 2021; Accepted 9 August 2021

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 μm 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. Aerosols can influence the cloud albedo, reducing the surface energy and the instability. Thornton et al. (2017) reported an increase of lightning activity over major oceanic shipping lanes. According to Thornton et al. (2017), ships in a convectively active region could serve as attachment points, increasing lightning activity. However, the widths of the areas with observed lightning enhancements are larger than the widths of the shipping lanes. Therefore, they also proposed that aerosols could have a role in the increase of lightning activity. Liu et al. (2020a) 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). Farias et al. (2008) and Kar et al. (2008) reported an enhancement in the ratio of −CG to +CG in highly contaminated areas in Brazil and South Korea, respectively. The ratio of IC to CG lightning is related with the thickness of the cold cloud region (Price and Rind, 1993), which can be affected by the concentration of aerosols, as reported by Lyons et al. (1998) in thunderstorms ingesting smoke from fires. Recently, Liu et al. (2020b) investigated the effect of aerosols in the IC/CG and the +CG/−CG ratio in oceanic thunderstorms. They showed that the invigoration of the mixed-phase development by aerosols near contaminated areas can enhance the IC/CG and the +CG/−CG ratios. These results suggest that aerosols play an important role in the electrical evolution and charge structure of the thunderstorm, as evident in the characteristics of lightning flashes. However, the effect of aerosols in the IC/CG and +CG/−CG ratios is inconclusive [Liu et al. (2020b) and references therein].

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. Liu et al. (2020a) 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 and Manzato, 2014; Anderson and 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). Scarce ventilation and low temperature at the Po Valley caused that aerosols are trapped for long periods (Squizzato et al., 2013). Especially northern Italy was significantly affected by the COVID-19 pandemic, leading to a dramatic reduction in the industrial activity, traffic and train transport during the COVID-19 lockdown declared by the Italian government between March 9th and May 18th 2020 (Cameletti, 1177) 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 μm 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) (Liu and Heckman, 2011; Zhu et al., 2017; Lapierre et al., 0313) 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) (Blakeslee et al., 2014, 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 and Christian, 2015) with a spatial resolution of 4 km (Blakeslee et al., 2020), covering latitudes between 54.3°N and 54.3°S (Blakeslee et al., 2020). The total DE of ISS-LIS ranges between 51% and 75% (Blakeslee et al., 2020).

ENTLN has a DE of about 90% for CG strokes over the U.S. (Zhu et al., 2017; Marchand et al., 2019; Lapierre et al., 0313). 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. LIS assorts contiguous events into groups, and clusters groups into flashes with a temporal criteria of 330 ms and a spatial criteria of 5.5 km (Mach et al., 2007). We compare ENTLN and ISS-LIS lightning data over the Po Valley with 1 s and 20 km as the matching criteria. 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. We show in Fig. 1 the investigated area of the Po Valley, including the location of the cities where aerosols measurements are investigated. The monthly average of the concentration of $PM_{2.5}$ during Spring 2020 in each of the adopted cities can be seen in Fig. S13 in the supporting material, indicating that the highest concentration of $PM_{2.5}$ during the lockdown were reported in Cremona and that the lowest concentrations were reported in Treviso and Torino.

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 hPa level between 2017 and 2020 over Europe (see the Figs. S6 and S7 in the supporting material) from images (NCEP/NCAR reanalysis data,) 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 and 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 (more information on this product can be found on https://www.eumetsat.int/media/7915). In this work, we collect 4-hourly CTH values over the Po Valley between March and October and between 2017 and 2020.

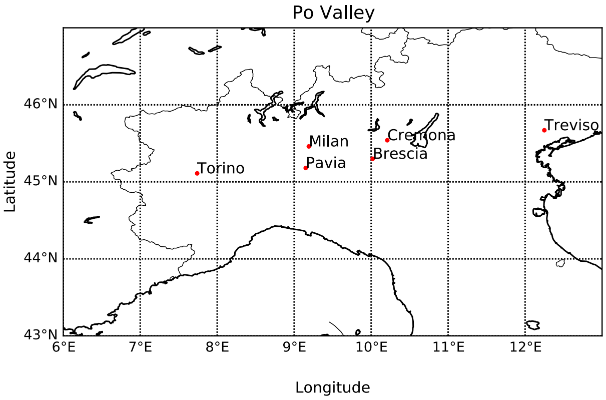

Fig. 1. Investigated area of the Po Valley, including the location of the cities where aerosols measurements are investigated.

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.

Fig. 2(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 including an error bar based on the standard variation of the daily data averaged in the monthly mean. 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. The error bars indicate that, despite the variability, the $PM_{2.5}$ concentration was significantly lower than the mean during the lockdown period.

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. 3. 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).

Fig. 2(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, February and December are not as reliable as in

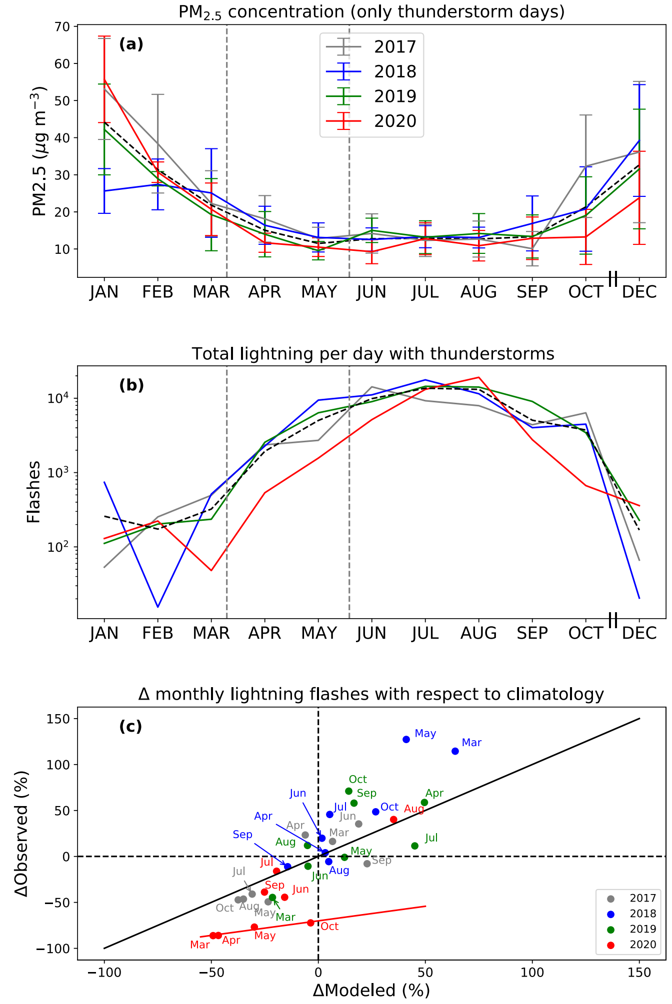

Fig. 2. Panel (a and b): Monthly average of (a) the concentration of PM$_{2.5}$ during days with thunderstorms averaged over all the stations in the selected Po Valley including an error bar based on the standard variation of the daily data averaged in the monthly mean and (b) the total lightning flashes 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). Vertical dashed lines indicate the begin and finish of the lockdown period. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

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$_{2.5}$ (Fig. 2 (a)) and/or by meteorology (see Figs. S2–S7 in the supplementary material). We 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., 0008). 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., 0008). 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 Fig. 2(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 and 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). 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 Fig. 2 (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 using the CAPE × P product, the CTH and flux of ice are −23%, −36% and −49%, respectively. We then propose the hypothesis that the decrease in PM$_{2.5}$ emissions during 2020 contributed to the 36±11% of the decrease in lightning activity, while the lightning parameterizations based on meteorology can only explain the 64%±11% 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. Fig. 3(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. In 2020, thunderstorms that developed in conditions when there were lower concentrations of PM$_{2.5}$ particles produced a lower number of lightning flashes than thunderstorms taking place in 2017, 2018 and 2019. We have fitted these data with a Gaussian distribution, obtaining that the peak is

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

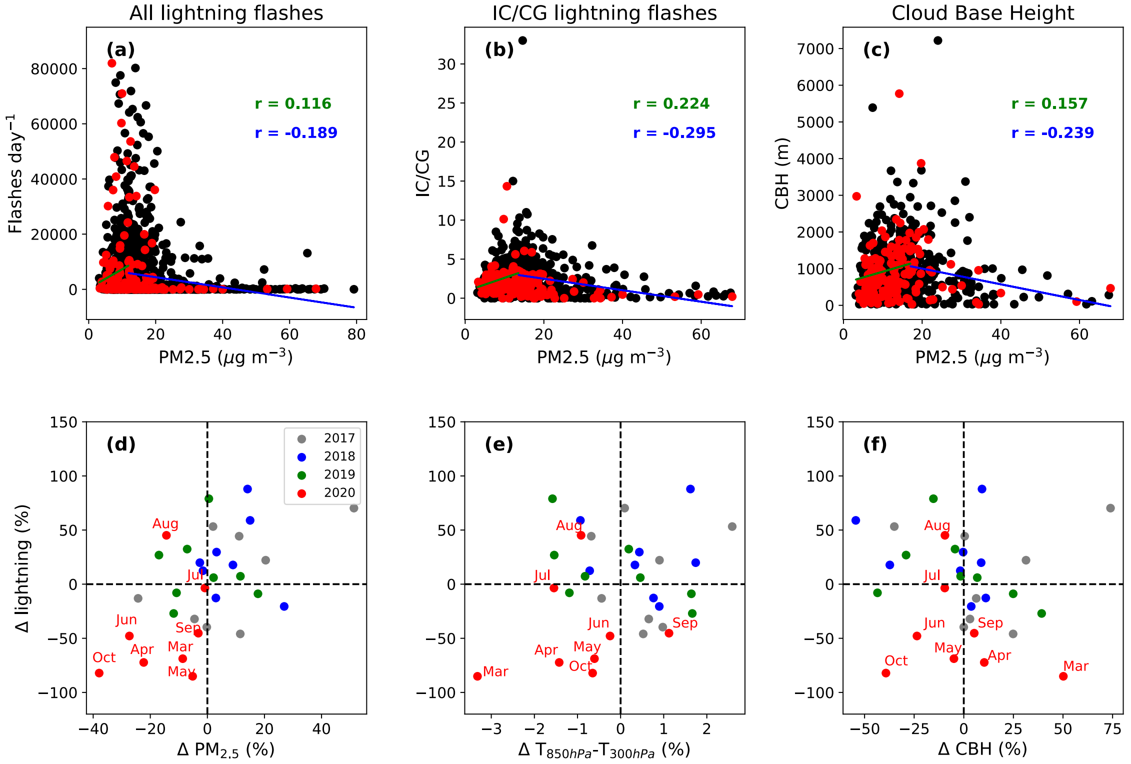

Fig. 3. Scatter plots of the (a) total number of flashes per day, (b) ratio of IC to CG lightning flashes and (c) CBH in thunderstorms versus the concentration of $PM_{2.5}$ particles for days with thunderstorms for 2017–2019 (black dots) and 2020 (red dots). We have fitted the data as explained in the 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. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

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; Altaratz et al., 2010; Tan et al., 2016; Shi et al., 2020).

We have calculated the Pearson's correlation coefficient for these variables (Fig. 3) from all years (2017–2020), 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. 3(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.

Fig. 3(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 Fig. 3(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 negative 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; Liu et al., 2020a).

Finally, Fig. 3(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 Fig. 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. Fig. 3(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 (Fig. 2). 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 (Fig. 2(a and b)) and cannot be fully attributed to meteorology (Fig. 2(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 $PM_{2.5}$ mass is heavily biased towards the largest particles in this class which might not be that abundant compared to smaller particles in the accumulation mode below 1 μm. Using size-resolved number concentrations (representing a measure of CCN concentration) would potentially lead to a cleaner signal. Unfortunately, such data is no widely available, therefore $PM_{2.5}$ has to be used instead. We think it is not a bad proxy since we expect that the size distribution typically might be relatively constant if the primary emission source does not change too much (Bigi and Ghermandi, 2011).

The scatter plot in Fig. 3(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 and 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 Fig. 3(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 CBH and a high concentration of aerosols. According to our results, the CBH in thunderstorms is linearly correlated with the concentration of $PM_{2.5}$ (see Fig. 3(c)). However, a deeper investigation of this possible relationship is out of the scope of this work. Combination of celiometer and satellite-based instruments measurements (Andersen et al., 2019) with lightning measurements over contaminated and non-contaminated areas could provide new information about the possible relationship between the concentration of aerosols, the CBH and lightning activity.

The effect of aerosols on lightning activity can be masked by meteorological conditions. However, Figs. 2(c) and 3(a–c) suggest that aerosols 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)

Finally, let us briefly discuss the relationship between lightning activity and the concentration of PM_{10} particles. We show in the supporting material (Figs. S11 and S12) similar plots as Fig. 2 and Fig. 3, but now showing the results using PM_{10} aerosol particles instead of $PM_{2.5}$ aerosol particles. These figures show that monthly variations in the concentration of PM_{10} with respect to the average during 2020 are similar as for $PM_{2.5}$ with the exception of March and September 2020. During March and September 2020, the concentration of PM_{10} with respect to the climatological average were positive, while they were negative for $PM_{2.5}$ particles. During March and September the first and the second waves of the pandemic led the authorities to implement new restrictions. Therefore, the effect of the restrictions manifests first in the concentration of lighter particles ($PM_{2.5}$) than in heavier particles (PM_{10}). In addition, we find that the threshold concentration of PM_{10} for increasing/decreasing lightning activity is 20 μg m^{-3} instead of 12 μg m^{-3}.

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 with respect to the climatological average (2017–2020).

2. ∼60±10% of the observed decrease in lightning activity is attributed to meteorology, and ∼40 ± 10% to the reduction in aerosol emissions.
3. 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.
4. 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 ($<12\ \mu g\ m^{-3}$) together with a negative correlation for higher concentration of $PM_{2.5}$ ($>12\ \mu g\ m^{-3}$), which might explain the observations stated in (1.).
5. 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).

Data availability

ISS-LIS data can be freely downloaded from https://ghrc.nsstc.nasa.gov/lightning/data/data_lis_iss.html. ENTLN data were obtained freely by request from Earth Networks (https://www.earthnetworks.com). The ERA5 meteorological data are freely accessible through Copernicus Climate Change Service (C3S) (2017): ERA5: Fifth generation of ECMWF atmospheric reanalyses of the global climate. Copernicus Climate Change Service Climate Data Store (CDS) https://cds.climate.copernicus.eu/cdsapp#!/home. EEA data can be freely downloaded from https://discomap.eea.europa.eu/map/fme/AirQualityExport.htm. All the analyzed EUMETSAT CTH product are freely accessible through the EUMETSAT Earth Observation Portal (https://eoportal.eumetsat.int/userMgmt/protected/welcome.faces). NCEP reanalysis data plotted in the supporting material can be downloaded from http://psl.noaa.gov/.

Declaration of Competing Interest

The authors declare no conflict of interest.

Acknowledgments

The authors would like to thank NASA for providing ISS-LIS lightning data, Earth Networks for providing ENTLN lightning data, ECMWF for providing the data of ERA5 forecasting models, EEA for providing air quality data, EUMETSAT for providing CTH product data and NCEP/NCAR for sharing atmospheric reanalysis data sets. Authors would also like to thank Daniel Sauer (Deutsches Zentrum für Luft-und Raumfahrt, DLR) for providing valuable comments on this manuscript.

FJPI acknowledges the sponsorship provided by the Federal Ministry for Education and Research of Germany through the Alexander von Humboldt Foundation. Additionally, this work was supported by the Spanish Ministry of Science and Innovation, under projects PID2019-109269RB-C43 and FEDER program. SS acknowledges a PhD research contract through the project PID2019-109269RB-C43. FJGV and SS acknowledge financial support from the State Agency for Research of the Spanish MCIU through the 'Center of Excellence Severo Ochoa' award for the Instituto de Astrofísica de Andaluca (SEV-2017-0709).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.atmosres.2021.105808.

References

Altaratz, O., Koren, I., Yair, Y., Price, C., 2010. Lightning response to smoke from Amazonian fires. Geophys. Res. Lett. 37 (7).

Andersen, H., Cermak, J., Solodovnik, I., Lelli, L., Vogt, R., 2019. Spatiotemporal dynamics of fog and low clouds in the Namib unveiled with ground-and space-based observations. Atmos. Chem. Phys. 19 (7), 4383–4392. https://doi.org/10.5194/acp-19-4383-2019.

Anderson, G., Klugmann, D., 2014. A European lightning density analysis using 5 years of ATDnet data. Nat. Hazards Earth Syst. Sci. 14 (4), 815–829. https://doi.org/10.5194/nhess-14-815-2014.

Bell, T.L., Rosenfeld, D., Kim, K.M., Yoo, J.M., Lee, M.I., Hahnenberger, M., 2008. Midweek increase in US summer rain and storm heights suggests air pollution invigorates rainstorms. J. Geophys. Res. Atmos. 113 (D2) https://doi.org/10.1029/2007JD008623.

Bigi, A., Ghermandi, G., 2011. Particle number size distribution and weight concentration of background urban aerosol in a Po valley site. Water Air Soil Pollut. 220 (1), 265–278. https://doi.org/10.1007/s11270-011-0752-6.

Bitzer, P.M., Burchfield, J.C., Christian, H.J., 2016. A Bayesian approach to assess the performance of lightning detection systems. J. Atmos. Ocean Technol. 33 (3), 563–578. https://doi.org/10.1175/JTECH-D-15-0032.1.

Bitzer, P.M., Christian, H.J., 2015. Timing uncertainty of the lightning imaging sensor. J. Atmos. Ocean Technol. 32 (3), 453–460. https://doi.org/10.1175/JTECH-D-13-00177.1.

Blakeslee, R., Lang, T., Koshak, W., Buechler, D., Gatlin, P., Mach, D., Stano, G., Virts, K., Walker, T., Cecil, D., et al., 2020. Three years of the lightning imaging sensor onboard the international space station: expanded global coverage and enhanced applications. Earth Space Sci. Open Arch. 35812, 83. https://doi.org/10.1029/2020JD032918.

Blakeslee, R.J., Christian, H.J., Stewart, M., Mach, D., Bateman, M., Walker, T.D., Buechler, D., Koshak, W., OBrien, S., Wilson, T., et al., 2014. Lightning Imaging Sensor (LIS) for the International Space Station (ISS): Mission Description and Science Goals.

Cameletti, M., 2020. The effect of corona virus lockdown on air pollution: evidence from the city of Brescia in Lombardia region (Italy). Atmos. Environ. 239, 117794. https://doi.org/10.1016/j.atmosenv.2020.117794.

Dye, J.E., Bansemer, A., 2019. Electrification in mesoscale updrafts of deep stratiform and anvil clouds in Florida. J. Geophys. Res. Atmos. 124 (2), 1021–1049. https://doi.org/10.1029/2018JD029130.

Farias, W., Pinto Jr., O., Naccarato, K., Pinto, I., 2009. Anomalous lightning activity over the metropolitan region of são paulo due to urban effects. Atmos. Res. 91 (2–4), 485–490. https://doi.org/10.1016/j.atmosres.2008.06.009.

Feudale, L., Manzato, A., 2014. Cloud-to-ground lightning distribution and its relationship with orography and anthropogenic emissions in the Po Valley. J. Appl. Meteorol. Climatol. 53 (12), 2651–2670. https://doi.org/10.1175/JAMC-D-14-00371.

Feudale, L., Manzato, A., Micheletti, S., 2013. A cloud-to-ground lightning climatology for North-Eastern Italy. Sci. Adv. Sc.. 10 (1), 77–84. https://doi.org/10.5194/asr-10-77-2013.

Finney, D., Doherty, R., Wild, O., Huntrieser, H., Pumphrey, H., Blyth, A., 2014. Using cloud ice flux to parametrise large-scale lightning. Atmos. Chem. Phys. 14 (23), 12665–12682. https://doi.org/10.5194/acp-14-12665-2014.

Gordillo-Vázquez, F.J., Pérez-Invernón, F.J., Huntrieser, H., Smith, A.K., 2019. Comparison of six lightning parameterizations in CAM5 and the impact on global atmospheric chemistry. Earth Space Sci. 6 (12), 2317–2346. https://doi.org/10.1029/2019EA000873.

Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horányi, A., Muñoz-Sabater, J., Nicolas, J., Peubey, C., Radu, R., Schepers, D., et al., 2020. The ERA5 global reanalysis. Q. J. R. Meteorol. Soc. 146 (730), 1999–2049. https://doi.org/10.1002/qj.3803.

Jones, C.D., Hickman, J.E., Rumbold, S.T., Walton, J., Lamboll, R.D., Skeie, R.B., Fiedler, S., Forster, P.M., Rogelj, J., Abe, M., et al., 2021. The climate response to emissions reductions due to COVID-19: initial results from CovidMIP. Geophys. Res. Lett. 48 (8) https://doi.org/10.1029/2020GL091883 e2020GL091883.

Kalnay, E., Kanamitsu, M., Kistler, R., Collins, W., Deaven, D., Gandin, L., Iredell, M., Saha, S., White, G., Woollen, J., et al., 1996. The NCEP/NCAR 40-year reanalysis project. Bull. Am. Meteorol. Soc. 77 (3), 437–472. https://doi.org/10.1175/1520-0477(1996)077<0437:TNYRP>2.0.CO;2.

Kar, S., Liou, Y.A., Ha, K.J., 2009. Aerosol effects on the enhancement of cloud-to-ground lightning over major urban areas of South Korea. Atmos. Res. 92 (1), 80–87. https://doi.org/10.1016/j.atmosres.2008.09.004.

Lapierre, J.L., Laughner, J.L., Geddes, J.A., Koshak, W.J., Cohen, R.C., Pusede, S.E., 2020. Observing US regional variability in lightning NO_2 production rates. J. Geophys. Res. Atmos. 125 (5) https://doi.org/10.1029/2019JD031362 e2019JD031362.

Liu, C., Heckman, S., 2011. The application of total lightning detection and cell tracking for severe weather prediction. In: 91st American Meteorological Society Annual Meeting, Germantown, Maryland 20874, USA: AWS Convergence Technologies, Inc., pp. 1–10.

Liu, L., Cheng, Y., Wang, S., Wei, C., Pöhlker, M.L., Pöhlker, C., Artaxo, P., Shrivastava, M., Andreae, M.O., Pöschl, U., et al., 2020a. Impact of biomass burning aerosols on radiation, clouds, and precipitation over the Amazon: relative importance of aerosol-cloud and aerosol-radiation interactions. Atmos. Chem. Phys. 20 (21), 13283–13301. https://doi.org/10.5194/acp-20-13283-2020.

Liu, Y., Guha, A., Said, R., Williams, E., Lapierre, J., Stock, M., Heckman, S., 2020b. Aerosol effects on lightning characteristics: a comparison of polluted and clean regimes. Geophys. Res. Lett. 47 (9) https://doi.org/10.1029/2019GL086825 e2019GL086825.

Lolli, S., Chen, Y.C., Wang, S.H., Vivone, G., 2020. Impact of meteorological conditions and air pollution on COVID-19 pandemic transmission in Italy. Sci. Rep. 10 (1), 1–15. https://doi.org/10.1038/s41598-020-73197-8.

Lyons, W.A., Nelson, T.E., Williams, E.R., Cramer, J.A., Turner, T.R., 1998. Enhanced positive cloud-to-ground lightning in thunderstorms ingesting smoke from fires. Science 282 (5386), 77–80.

Mach, D.M., Christian, H.J., Blakeslee, R.J., Boccippio, D.J., Goodman, S.J., Boeck, W.L., 2007. Performance assessment of the optical transient detector and lightning imaging sensor. J.. Geophys. Res. Atmos. 112 (D9).

Mansell, E.R., Ziegler, C.L., 2013. Aerosol effects on simulated storm electrification and precipitation in a two-moment bulk microphysics model. J. Atmos. Sci. 70 (7), 2032–2050. https://doi.org/10.1175/JAS-D-12-0264.1.

Marchand, M., Hilburn, K., Miller, S.D., 2019. Geostationary lightning mapper and earth networks lightning detection over the contiguous United States and dependence on flash characteristics. J. Geophys. Res. Atmos. 124 (21), 11552–11567. https://doi.org/10.1029/2019JD031039.

Mertens, M., Jöckel, P., Matthes, S., Nützel, M., Grewe, V., Sausen, R., 2021. COVID-19 induced lower-tropospheric ozone changes. Environ. Res. Lett. https://doi.org/10.1088/1748-9326/abf191.

Naccarato, K., Pinto Jr., O., Pinto, I., 2003. Evidence of thermal and aerosol effects on the cloud-to-ground lightning density and polarity over large urban areas of southeastern Brazil. Geophys. Res. Lett. 30 (13) https://doi.org/10.1029/2003GL017496.

Nakajima, T., Higurashi, A., Kawamoto, K., Penner, J.E., 2001. A possible correlation between satellite-derived cloud and aerosol microphysical parameters. Geophys. Res. Lett. 28 (7), 1171–1174. https://doi.org/10.1029/2000GL012186.

Neto, O.P., Pinto, I.R., Pinto Jr., O., 2020. Lightning during the COVID-19 pandemic in Brazil. J. Atmos. Sol. Terr. Phys. 211, 105463. https://doi.org/10.1016/j.jastp.2020.105463.

Orville, R.E., Huffines, G., Nielsen-Gammon, J., Zhang, R., Ely, B., Steiger, S., Phillips, S., Allen, S., Read, W., 2001. Enhancement of cloud-to-ground lightning over Houston, Texas. Geophys. Res. Lett. 28 (13), 2597–2600. https://doi.org/10.1029/2001GL012990.

Pérez-Invernón, F.J., Huntrieser, H., Soler, S., Gordillo-Vázquez, F.J., Pineda, N., Navarro-González, J., Reglero, V., Montanyà, J., van der Velde, O., Koutsias, N., 2021. Lightning-ignited wildfires and long-continuing-current lightning in the Mediterranean basin: preferential meteorological conditions. Atmos. Chem. Phys. Discuss. 1–43. https://doi.org/10.5194/acp-2021-125.

Price, C., Rind, D., 1992. A simple lightning parameterization for calculating global lightning distributions. J. Geophys. Res. Atmos. 97 (D9), 9919–9933. https://doi.org/10.1029/92JD00719.

Price, C., Rind, D., 1993. What determines the cloud-to-ground lightning fraction in thunderstorms? Geophys. Res. Lett. 20 (6), 463–466. https://doi.org/10.1029/93GL00226.

Romps, D.M., Charn, A.B., Holzworth, R.H., Lawrence, W.E., Molinari, J., Vollaro, D., 2018. Cape times p explains lightning over land but not the land-ocean contrast. Geophys. Res. Lett. 45 (22), 12–623. https://doi.org/10.1029/2018GL080267.

Romps, D.M., Seeley, J.T., Vollaro, D., Molinari, J., 2014. Projected increase in lightning strikes in the United States due to global warming. Science 346, 851. https://doi.org/10.1126/science.1259100.

Rosenfeld, D., Sherwood, S., Wood, R., Donner, L., 2014. Climate effects of aerosol–cloud interactions. Science 343 (6169), 379–380. https://doi.org/10.1126/science.1247490.

Rust, W.D., MacGorman, D.R., 2002. Possibly inverted-polarity electrical structures in thunderstorms during STEPS. Geophys. Res. Lett. 29 (12) https://doi.org/10.1029/2001GL014303, 12-1.

Saunders, C., 1993. A review of thunderstorm electrification processes. J. Appl. Meteorol. Climatol. 32 (4), 642–655. https://doi.org/10.1175/1520-0450(1993)032<0642:AROTEP>2.0.CO;2.

Saunders, C., 2017. Thunderstorm electrification. Handbook of Atmospheric Electrodynamics. CRC Press, pp. 61–92. https://doi.org/10.1002/j.1477-8696.1988.tb04957.x.

Schleidt, K., 2013. Inspired air quality reporting. In: Hřebíček, J., Schimak, G., Kubásek, M., Rizzoli, A.E. (Eds.), Environmental Software Systems. Fostering Information Sharing. Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 439–450.

Schmetz, J., Pili, P., Tjemkes, S., Just, D., Kerkmann, J., Rota, S., Ratier, A., 2002. An introduction to Meteosat Second Generation (MSG). Bull. Am. Meteorol. Soc. 83 (7), 977–992. https://doi.org/10.1175/1520-0477(2002)083<0977:AITMSG>2.3.CO;2.

Shi, Z., Song, C., Liu, B., Lu, G., Xu, J., Van Vu, T., Elliott, R.J., Li, W., Bloss, W.J., Harrison, R.M., 2021. Abrupt but smaller than expected changes in surface air quality attributable to COVID-19 lockdowns. Sci. Adv. 7 (3) https://doi.org/10.1126/sciadv.abd6696 eabd6696.

Shi, Z., Wang, H., Tan, Y., Li, L., Li, C., 2020. Influence of aerosols on lightning activities in central eastern parts of China. Atmos. Sci. Lett. 21 (2), e957. https://doi.org/10.1002/asl.957.

Showalter, A.K., 1953. A stability index for thunderstorm forecasting. Bull. Am. Meteorol. Soc. 34 (6), 250–252.

Squizzato, S., Masiol, M., Brunelli, A., Pistollato, S., Tarabotti, E., Rampazzo, G., Pavoni, B., 2013. Factors determining the formation of secondary inorganic aerosol: a case study in the Po Valley (Italy). Atmos. Chem. Phys. 13 (4), 1927–1939. https://doi.org/10.5194/acp-13-1927-2013.

Stolz, D.C., Rutledge, S.A., Pierce, J.R., van den Heever, S.C., 2017. A global lightning parameterization based on statistical relationships among environmental factors, aerosols, and convective clouds in the TRMM climatology. J. Geophys. Res. Atmos. 122 (14), 7461–7492. https://doi.org/10.1002/2016JD026220.

Sun, M., Liu, D., Qie, X., Mansell, E.R., Yair, Y., Fierro, A.O., Yuan, S., Chen, Z., Wang, D., 2021. Aerosol effects on electrification and lightning discharges in a multicell thunderstorm simulated by the WRF-ELEC model. Atmos. Chem. Phys. Discuss. 1–37. https://doi.org/10.5194/acp-2020-1284.

Takahashi, T., 1978. Riming electrification as a charge generation mechanism in thunderstorms. J. Atmos. Sci. 35 (8), 1536–1548.

Takahashi, T., 1984. Thunderstorm electrification – a numerical study. J. Atmos. Sci. 41 (17), 2541–2558. https://doi.org/10.1175/1520-0469(1984)041<2541:TENS>2.0.CO;2.

Tan, Y., Peng, L., Shi, Z., Chen, H., 2016. Lightning flash density in relation to aerosol over Nanjing (China). Atmos. Res. 174, 1–8. https://doi.org/10.1016/j.atmosres.2016.01.009.

Tao, W.K., Chen, J.P., Li, Z., Wang, C., Zhang, C., 2012. Impact of aerosols on convective clouds and precipitation. Rev. Geophys. 50 (2) https://doi.org/10.1029/2011RG000369.

Thornton, J.A., Virts, K.S., Holzworth, R.H., Mitchell, T.P., 2017. Lightning enhancement over major oceanic shipping lanes. Geophys. Res. Lett. 44 (17), 9102–9111. https://doi.org/10.1002/2017GL074982.

Tsenova, B.D., Barakova, D., Mitzeva, R., 2017. Numerical study on the effect of charge separation at low cloud temperature and effective water content on thunderstorm electrification. Atmos. Res. 184, 1–14. https://doi.org/10.1016/j.atmosres.2016.09.011.

Wang, W., Zhang, T., Pan, Z., 2019. Four-year ground-based observations of the aerosol effects on cloud base height in Wuhan, China. Atmos. Pollut. Res. 10 (5), 1531–1535. https://doi.org/10.1016/j.apr.2019.05.001.

Williams, E., Stanfill, S., 2002. The physical origin of the land-ocean contrast in lightning activity. Comptes Rendus Physique 3 (10), 1277–1292. https://doi.org/10.1016/S1631-0705(02)01407-X.

Zhu, Y., Rakov, V., Tran, M., Stock, M., Heckman, S., Liu, C., Sloop, C., Jordan, D., Uman, M., Caicedo, J., et al., 2017. Evaluation of ENTLN performance characteristics based on the ground truth natural and rocket-triggered lightning data acquired in Florida. J. Geophys. Res. Atmos. 122 (18), 9858–9866. https://doi.org/10.1002/2017JD027270.

Zoran, M.A., Savastru, R.S., Savastru, D.M., Tautan, M.N., 2020. Assessing the relationship between surface levels of $PM_{2.5}$ and PM_{10} particulate matter impact on COVID-19 in Milan, Italy. Sci. Total Environ. 738, 139825. https://doi.org/10.1016/j.scitotenv.2020.139825.