Abstract
The data of lightning flash count, rainfall, radar reflectivity, vertical wind shear (WS), surface dew point temperature (DP) and particulate matter up to 10 μm in size (PM10) over Guilin, China from July 2010 to December 2019 were studied to check whether aerosol invigoration effect (AIV) exists in the study area. It was found that convective rainfall fluctuates less when compared with lightning in convective system. A hypothesis was put forward that the difference in fluctuations between convective rainfall and lightning is attributed to AIV. To test this hypothesis, lightning yield, which is defined as the ratio between lightning and rainfall, was analyzed. It was found that lightning yield has a positive correlation with PM10 when WS is low and DP is high for convective precipitation. It was also found that for the weak WS cases, when aerosol conditions are shifted from super pristine to the optimal concentration ($N_{op}$), lightning yield increases with increasing PM10; whereas for concentrations greater than $N_{op}$, lightning yield decreases with increasing PM10. $N_{op}$ would be larger for higher DP. The results are in line with the previous studies showing that AIV depends strongly on weak wind shear and/or warm cloud base. This suggests that AIV exists in the study area, and suggests that the hypothesis is reasonable, and lightning yield can be used as a surrogate to study AIV.

KEYWORDS
aerosol invigoration effect, lightning, precipitation, surface dew point temperature, vertical wind shear

1 | INTRODUCTION

Aerosols affect cloud properties and precipitation in complex ways (IPCC, 2013; Jiang et al., 2019; Zhang et al., 2020). Aerosols can scatter and/or absorb incoming sunlight to exert radiative forcing which perturbs atmospheric stability, this being known as the direct aerosol effect which cools the earth’s surface (Charlson et al., 1992; Grandey et al., 2016; Reddy et al., 2005). In addition, enhanced solar heating by aerosol can warm the atmosphere which causes the evaporation of cloud droplets and the reduction in cloud cover. This is being known as the semi-direct effect (Ackerman et al., 2000; Koch & Genio, 2010; McFarquhar et al., 2011). Aerosols can also serve as cloud condensation nuclei (CCN) and ice nuclei (IN) and change the cloud microphysical processes, which is known as the indirect aerosol effect. One of the indirect effects is that additional aerosols in warm clouds can increase cloud nucleus concentrations, hence, increase more and, for a constant cloud liquid water path...
(LWP), smaller cloud droplets, which leads to increasing cloud albedo and thus radiatively cools the surface. It is known as the Twomey effect (Albrecht, 1989; Twomey, 1977; Zhao et al., 2012). Besides, microphysical changes caused by aerosols can alter the microphysical, dynamic and thermodynamic processes in clouds and the ambient atmosphere. For example, cloud droplet number concentration and size vary with increasing aerosols (Lohmann & Feichter, 2005; Ma et al., 2018; Zhao & Garrett, 2015), which affects cloud lifetime (the cloud lifetime effect) (Chakraborty et al., 2016; Guo et al., 2016; Lohmann & Lesins, 2002), influences glaciation of clouds (the glaciation indirect effect) (Lohmann, 2002; Phillips et al., 2002; Senf & Deneke, 2017) and invigorates convection (the aerosol invigoration effect, AIV) (Altaratz et al., 2014; Dagan et al., 2015; Storer & Van den Heever, 2013), and thus affects the evolutions of cloud, precipitation and lightning (Hu & Liu, 2013; Lal et al., 2018; Tao et al., 2012).

Among the various aerosol-cloud-precipitation interactions, AIV is believed to be a challenging question because compelling evidence for the invigoration effect is difficult to obtain (Kant et al., 2021; Koren et al., 2014). Increasing aerosols in individual deep convective clouds (DCCs) often produce more but smaller cloud droplets; smaller drops do not precipitate before reaching the supercooled levels, where they freeze onto ice precipitation which falls and melts at lower levels; it releases latent heat at higher altitudes and invigorates convections, and thus brings higher cloud tops, greater cloud cover and slows dissipation of the anvil of DCCs (Andreae et al., 2004). Previous studies have found that cloud fraction, cloud top height, lightning activity and rain rate increase with increasing aerosol loading in many places (e.g., Kaufman et al., 2005; Storer et al., 2014; Yuan et al., 2011), and attributed the phenomenon to AIV. However, it is largely debated whether the phenomenon is due to AIV, or whether it should be explained by other reasons, such as meteorological co-variation, hygroscopic growth of aerosols, cloud processing or in-cloud nucleation of aerosols, wet scavenging and so on (Loeb & Schuster, 2008; Quaas et al., 2010; Twohy et al., 2009). Besides, some studies, either by observations (Smith et al., 2003; Williams et al., 2002) or by numerical models (Jiang & Feingold, 2006; Xue et al., 2008), have shown that higher aerosol concentration cannot invigorate convections or AIV has a non-monotonic change with increasing aerosols. It was also found that the variety of environments, as well as the synoptic-scale weather systems in which mesoscale convective systems (MCCs) are embedded, could play important roles in regulating AIV (Kalina et al., 2014; Zhang et al., 2020). In general, aerosol effect represents only one of many effects affecting convective activity and is not the strongest one (Khain, 2009), and these effects are often intertwined (Fuchs et al., 2015). This makes disentangling AIV from other effects a difficult task. Till now AIV is still poorly understood and is one challenging problem in studying anthropogenic climate forcing (IPCC, 2013; Zhang et al., 2020).

Thunderstorm-mediated lightning and intense rainfall events, which often relate to fatalities and injuries, are among the most devastating hazards, especially in developing countries where many people spend time outdoors in manual labor-intensive agriculture, and where infrastructure, emergency management, public education and weather forecasting service are poor (Adhikari, 2021; Dewan et al., 2017; Gatlin et al., 2021; Holle et al., 2019). The positive correlation between lightning and rainfall has been reported by many papers (e.g., Battan, 1965; Dewan et al., 2018; Liou & Kar, 2010). According to AIV theory, aerosols could suppress warm rain formation, and it allows more cloud water being lifted higher in the atmosphere and enhances convection (Fan et al., 2016), and thus changes lightning discharge which has a positive relation with convection rate (Siingh et al., 2015). Lightning enhancement by aerosols has been revealed by satellite and in situ measurements (e.g., Lal et al., 2018; Stolz et al., 2017; Wang et al., 2018). While for rainfall, the amount of precipitation balances the amount of evaporation at the global scale; and the consequence of aerosols suppressing precipitation from shallow clouds is compensation of precipitation increase from deeper clouds, which is not only at the global scale but also at the cloud scale (Rosenfeld et al., 2008). So it is expected that rainfall fluctuates less when compared with lightning in a convective system according to AIV theory, and thus the study of the ratio between lightning and precipitation might sharpen AIV. Roles of the parameters vertical wind shear and temperature, which have been pointed out to be important affecting factors in regulating AIV (Chen et al., 2020; Fan et al., 2009; Fan et al., 2012), could be revealed by analyzing the relation between these parameters and the ratio.

2 DATA AND METHODOLOGY

Guilin, a city in Guangxi province, South China, is the area studied. Lightning data, which is defined as total cloud-to-ground (CG) lightning flash count, was observed by a local lightning monitoring system consisting of 11 lightning sensors to provide the coverage of lightning flashes for the entire Guangxi province (see Figure 1a). The median error of the location accuracy and the detection efficiency are <1 km and above 90%, respectively. The Improved Performance through Combined Technology (IMPACT) method (Cummins et al., 1998; Xie...
et al., 2015), which combines the direction finding and time of arrival technology to determine the lightning location, was used.

The ratio between lightning flash count and precipitation will be studied, and is named as lightning yield. It is computed as follows.

\[
\text{Lightning yield} = \frac{\text{number of total CG flash counts during a certain time period}}{\text{rainfall over the same time period}}
\]  

where “a certain time period” would be a month and an hour respectively to study monthly lightning yield and hourly lightning yield in this study.

It was reported that convective clouds typically develop from convective thermals rooted in the lowest part of the planetary boundary layer, and thermals from the surface layer can rise without being diluted to the top of the mixed layer and form clouds, and thus surface dew point temperature (DP) is a good estimate for cloud base temperature (Fuchs et al., 2015; Lenderink et al., 2021; Staiger & Matzarakis, 2010; Zheng & Rosenfeld, 2015). Considering that cloud base temperature, which plays an important role on AIV (Li et al., 2011; Varble, 2018), is lacked in the study area, DP, which was observed at 1.5 meters above surface, is used as a surrogate.

It is believed that PM$_{10}$ (particulate matter up to 10 μm in size concentration) is better than aerosol optical depth (AOD) in studying aerosol-precipitation interaction because the former could be observed under all-sky conditions while the latter could be measurable only under cloud-free conditions; besides, PM$_{10}$ is sufficient for studying aerosol effect on convective systems over South China (Guo et al., 2016). Thus, PM$_{10}$ concentration data was chosen as a proxy for CCN in this study. The PM$_{10}$ concentration data are the mean of the observed values in five environmental stations over Guilin city (see Figure 1b), all of which were observed at 15 m above surface following the technical specifications for installation and acceptance of ambient air quality continuous automated monitoring system in China (Chinese Ecology and Environment Ministry, 2013). However, hourly PM$_{10}$ is not available and thus daily PM$_{10}$ is used as a surrogate. Considering that it needs a period (usually several hours and changing under various environmental conditions) for aerosol particles expanding from the surface to cloud level to act as in-cloud droplet number concentration (Han et al., 2008; Huang et al., 2009; Kong et al., 2009); and also considering that daily PM$_{10}$ changes less when compared with hourly PM$_{10}$ due to hourly-scale wet scavenging, and thus would be more suitable than hourly PM$_{10}$ in this study for we are studying aerosol effect on precipitation rather than precipitation effect on aerosol; daily PM$_{10}$ is used to study hourly-scale lighting/rainfall following Li et al. (2018), for example, if the daily PM$_{10}$ in 1 day is 0.04 mg·m$^{-3}$, all of the 24 h PM$_{10}$ in this day are taken as 0.04 mg·m$^{-3}$.

The radar composite reflectivity data, containing the maximum reflectivity value of all layers, was observed by
a Doppler radars located at Guilin weather station, that is, coincident with the chosen observation site (see Figure 1a). Besides, vertical wind shear (WS) is defined as wind difference between 850 and 200 hPa following Hoyos et al. (2006), and is calculated by the NCEP reanalysis data from NOAA National Center for Environmental Prediction Reanalysis Information. However, the NCEP reanalysis data are available only on 02, 08, 14 and 20 LST (LST = UTC + 8 h), and thus hourly WS in other hours were calculated by interpolation using the data on 02/08/14/20 LST.

The data of rainfall, DP and radar composite reflectivity, obtained from China Meteorological Information Center, were observed in Guilin weather station (longitude 110.30°E, latitude 25.33°N, altitude 164.4 m, World Meteorological Organization ID code: 57957). The lightning data were obtained from China Meteorological Information Center too; a spatial scale of 0.1°latitude × 0.1°longitude (about 100 km²) surrounding Guilin weather station was selected to find out the CG lightning flash counts following previous papers (Li et al., 2018; Liou & Kar, 2010). The PM$_{10}$ concentration data were obtained from Guangxi Environmental Protection Bureau. The data have undergone quality control checks at China Meteorological Information Center and Guangxi Environmental Protection Bureau. The data from July 2010 to December 2019 are analyzed in this study. Data availability is above 99.5% for the variables CG lightning, rainfall, PM$_{10}$, WS, DP, and is above 81.5% for the variable radar reflectivity.

### 3 | SEASONAL VARIATION

The seasonal variation is studied based on monthly data. It is found from Figure 2 that all variables have obvious seasonal variations. Lightning flash count and total rain are high in warm seasons (April–October) and are low in cold seasons (November–March), and it is attributed to the seasonal variations of convective available potential energy (CAPE) and surface temperature (Singh et al., 2014). A similar seasonal variation occurs in radar reflectivity which has a close relation with lightning and precipitation (Stolz et al., 2015). Lightning yield is high in warm seasons and is low in cold seasons too, and it is because that the surface heating is more in warm seasons than that in cold seasons; the excessive surface heating enhances the magnitude of CAPE and its other characteristics in the atmosphere which in turn fosters thunderstorm generation (Liou & Kar, 2010). DP is also high in warm seasons and is low in cold seasons, and it is attributed to the seasonal variation of solar radiation which changes monthly air temperature and then changes monthly DP (Tan et al., 2016).

On the contrary, PM$_{10}$ is low in warm seasons and is high in cold seasons, and it is attributed to unstable
atmospheric conditions and rainy weather that are favorable for the dispersion and scavenging of airborne particulate matter in warm seasons (Li et al., 2018). WS is low in warm seasons and is high in cold seasons too, and it is due to the various weather systems. In warm seasons, the atmospheres at both low and high altitudes are often controlled by the western Pacific subtropical high, and thus, the winds at low and high altitudes are relatively coincident. While in cold seasons, the atmospheres are often affected by both Mongolian high from the North and Warm and humid air flow in the bay of Bengal from the South, and thus the wind shear is relatively higher.

4 | DIFFERENT FLUCTUATIONS OF LIGHTNING AND CONVECTIVE RAINFALL IN CONVECTIVE SYSTEM

AIV in convective system will be studied by analyzing lightning and convective rainfall using hourly data in the following sections. Before discussing in detail lightning and convective rainfall of convective system, the hourly cases must be analyzed to remove non-convective precipitation. This work is done by the following principles: to study convective system, non-convective precipitation cases should be removed as much as possible; however, if the rainfall used for analysis is only a tiny fraction of the total rainfall, the significance of these findings will be limited. Considering that convection is relatively weak if radar reflectivity is below 30 dBZ (Ackerman et al., 2015; Stolz et al., 2015), an hourly precipitation case is defined as a convective precipitation case when hourly rainfall is above zero and hourly radar reflectivity is not less than 30 dBZ, while an hourly precipitation case is defined as a non-convective precipitation case when hourly rainfall is above zero and hourly radar reflectivity is below 30 dBZ. The accumulative amounts of convective rainfall, total rainfall and the proportion of convective rainfall to total rainfall during the studied time are calculated, and are presented in Table 1. It shows that total rainfall is 15,918 mm during July 2010 to December 2019, in which 11,306 mm is convective rainfall, that is, 71.0% of the total rainfall will be studied when the convective rainfall is analyzed. This result suggests that studying convective precipitation could roughly clarify the variation of total rainfall in the study area.

To further clarify the difference between the non-convective precipitation cluster and the convective precipitation cluster, sample number and mean value of rainfall/lightning flash count for these two clusters are presented in Table 2. The mean rainfall of one case is 0.77 mm for the non-convective precipitation cluster, which is lower than that for the convective precipitation cluster (4.98 mm). When lightning is studied for the non-convective precipitation cluster, it is found that the mean lightning flash count is 0.07 counts, that is, about one count is observed for every 10 cases. This is very limited when compared with that of the convective precipitation cluster which is 2.33 counts, that is, lightning occurs mainly in convective system rather than non-convective system.

Based on the results above, it is concluded that the use of the hourly cases with rainfall >0 mm and radar reflectivity ≥30 dBZ is reasonable when studying the convective system in the study area. Then, the hourly convective cases are stratified into 10 clusters by PM10 value. The thresholds of PM10 are given to ensure that the sample numbers of the clusters are roughly equal, and are presented in Table 3. Mean value and standard deviation for convective rainfall/lightning in each cluster are presented in Table 3 too. For convective rainfall, the mean value ranges from 3.0 to 6.9 mm, and the standard deviation ranges from 5.3 to 7.9 mm. For lightning flash count, the mean value is from 1.1 to 3.8, and the standard deviation is from 4.0 to 27.5. Ratio between standard deviation and mean value (i.e., ratio = standard deviation/mean) is calculated for both convective rainfall and lightning flash count, and is also presented in Tables 3. It is shown that the ratio is 114.5%–216.7% for convective rainfall, and is 350.0%–723.7% for lightning flash count. Based on these results, it is concluded that convective rainfall fluctuates much less when compared with lightning flash count for every PM10 segment.

To explain the phenomenon, a possible hypothesis is put forward as follows. According to AIV theory, aerosols could enhance lightning discharge which has a positive relation with convection rate (Singh et al., 2015). While for rainfall, the consequence of aerosols suppressing precipitation from shallow clouds is a compensation of precipitation increase from deeper clouds (Rosenfeld et al., 2008; Storer & Van den Heever, 2013), that is, convective rainfall would vary less with increasing aerosols when compared with lightning because compensation mechanism exists in convective precipitation rather than lightning. If this hypothesis is right, lightning yield, which is defined as the ratio between lightning and

| TABLE 1 | Convective rainfall, total rainfall and proportion of convective rainfall to total rainfall from July, 2010 to December, 2019 |
|------------------------------|------------------|
| Convective rainfall (mm)     | 11,306           |
| Total rainfall (mm)          | 15,918           |
| Proportion (%)               | 71.0             |
Comparison of the non-convective precipitation cluster and convection precipitation cluster

Sample number (

The correlation of hourly lightning yield versus PM10

and PM10 of the weak WS cluster, a scatter plot of light-

strong WS (WS > 26 m

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follows.

shows that lightning yield tends to increase when PM10

= ’0 mm and radar reflectivity ≥30 dBZ and hourly rainfall >0 mm. Sample number (N), mean value of rainfall and mean value of lightning flash count are presented.

TABLE 3 Sample number (N), mean value (mean), standard deviation (SD) and ratio between standard deviation and mean value (ratio = SD/mean value) of both convective rainfall and lightning flash count

| Cluster name | Rainfall | Lightning flash count |
|--------------|----------|-----------------------|
|              | Mean  | SD    | Ratio (%) | Mean (fl mm\(^{-1}\)) | SD (fl mm\(^{-1}\)) | Ratio (%) |
| 1 (PM\(_{10}\) ≤ 0.0200 mg m\(^{-3}\)) | 263   | 6.9  | 7.9 | 114.5 | 3.8 | 27.5 | 723.7 |
| 2 (PM\(_{10}\): 0.0201–0.0240 mg m\(^{-3}\)) | 224   | 6.3  | 7.9 | 125.4 | 1.1 | 4.0 | 363.6 |
| 3 (PM\(_{10}\): 0.0241–0.0290 mg m\(^{-3}\)) | 220   | 5.5  | 7.4 | 134.5 | 1.5 | 7.3 | 486.7 |
| 4 (PM\(_{10}\): 0.0291–0.0330 mg m\(^{-3}\)) | 220   | 5.1  | 6.7 | 131.4 | 1.7 | 6.3 | 370.6 |
| 5 (PM\(_{10}\): 0.0331–0.0380 mg m\(^{-3}\)) | 209   | 4.9  | 7.9 | 161.2 | 2.9 | 13.6 | 469.0 |
| 6 (PM\(_{10}\): 0.0381–0.0440 mg m\(^{-3}\)) | 236   | 5.0  | 6.9 | 138.0 | 1.6 | 5.6 | 350.0 |
| 7 (PM\(_{10}\): 0.0441–0.0515 mg m\(^{-3}\)) | 228   | 4.7  | 7.6 | 161.7 | 2.6 | 10.0 | 384.6 |
| 8 (PM\(_{10}\): 0.0516–0.0635 mg m\(^{-3}\)) | 221   | 4.0  | 5.3 | 132.5 | 3.2 | 16.1 | 503.1 |
| 9 (PM\(_{10}\): 0.0636–0.0850 mg m\(^{-3}\)) | 225   | 4.0  | 6.3 | 157.5 | 3.5 | 16.3 | 465.7 |
| 10 (PM\(_{10}\) ≥ 0.0851 mg m\(^{-3}\)) | 225   | 3.0  | 6.5 | 216.7 | 1.3 | 8.9 | 684.6 |

Note: The data are grouped by the values of PM\(_{10}\). A case is used only when hourly radar reflectivity ≥30 dBZ and hourly rainfall >0 mm.

TABLE 4 The correlation of hourly lightning yield versus PM\(_{10}\)

| Cluster | Correlation coefficient (r) |
|---------|----------------------------|
| Weak WS (WS ≤ 13 m s\(^{-1}\)) | N = 871, b = 61.3, R = 0.182, p < 0.001 |
| Medium WS (13 m s\(^{-1}\) < WS ≤ 26 m s\(^{-1}\)) | N = 741, b = −5.0, R = −0.024, p > 0.1 |
| Strong WS (WS > 26 m s\(^{-1}\)) | N = 833, b = 1.3, R = 0.025, p > 0.1 |
| Weak WS, low DP (WS ≤ 13 m s\(^{-1}\), DP ≤ 22.8°C) | N = 290, b = 12.1, R = 0.200, p < 0.001 |
| Weak WS, medium DP (WS ≤ 13 m s\(^{-1}\), 22.8°C < DP ≤ 24.1°C) | N = 298, b = 69.8, R = 0.205, p < 0.001 |
| Weak WS, high DP (WS ≤ 13 m s\(^{-1}\), DP > 24.1°C) | N = 283, b = 117.0, R = 0.232, p < 0.001 |

Note: The data are grouped by WS and DP. Sample number (N), regression coefficient (b) of regression equation, correlation coefficient (R) and significance level (p) are presented. A case is used only hourly radar reflectivity ≥30 dBZ and hourly rainfall >0 mm.

For studying the role of WS in the dependence of hourly lightning yield on PM\(_{10}\), the hourly cases with rainfall >0 mm and radar reflectivity ≥30 dBZ are grouped into three clusters by different WS. The values of 13 and 26 m s\(^{-1}\) were used as thresholds of WS to ensure that the sample numbers are roughly equal for the three clusters, that is, sample number is 871 for the weak WS (WS ≤ 13 m s\(^{-1}\)) cluster, is 741 for the medium WS (13 m s\(^{-1}\) < WS ≤ 26 m s\(^{-1}\)) cluster, and is 833 for the strong WS (WS > 26 m s\(^{-1}\)) cluster (see Table 4).

To analyze the correlation between lightning yield and PM\(_{10}\) of the weak WS cluster, a scatter plot of lightning yield versus PM\(_{10}\) is presented in Figure 3a, which shows that lightning yield tends to increase when PM\(_{10}\) increases. The correlation coefficient R is 0.182 and the significance level p is below 0.001 (see in Figure 3a and Table 4). The result suggests that increasing aerosols would enhance statistically lightning yield when WS is weak.
For quantifying the effect of PM$_{10}$ on lightning yield in this cluster, linear regression curve and regression equation are studied (presented in Figure 3a and Table 4 too). The regression coefficient ($b$) of regression equation is 61.3, that is to say, lightning yield will increase about 61 fl mm$^{-1}$ when PM$_{10}$ increases 1 mg m$^{-3}$.

Following what has been performed on the weak WS (WS $\leq$ 13 m s$^{-1}$) cluster, the medium WS (13 m s$^{-1}$ $<$ WS $\leq$ 26 m s$^{-1}$) and the strong WS (WS $>$ 26 m s$^{-1}$) clusters are analyzed too. The results presented in Figure 3b, c and Table 4 show that correlation coefficient $R$ is 0.024 and 0.025 for the medium WS and the strong WS clusters, respectively. Significance level $p$ is above 0.1 for both of these two clusters. It suggests that the correlations between lightning yield and PM$_{10}$ are not statistically significant. These results suggest that lightning yield increases obviously with aerosols in weaker WS conditions rather than stronger WS conditions.

6 | DEPENDENCE OF LIGHTNING YIELD ON PM$_{10}$, WS AND DP

In this section, the joint effects of both WS and DP in the dependence of lightning yield on PM$_{10}$ will be studied. Considering that lightning yield increases significantly with increasing PM$_{10}$ only for the weak WS clusters, the study of joint effects of both WS and DP will only use the weak WS cases.

The 871 weak WS cases are grouped into three clusters by DP with thresholds 22.8°C and 24.1°C to ensure that the sample numbers are roughly equal for the three clusters, that is, the weak WS, low DP (WS $\leq$ 13 m s$^{-1}$, DP $\leq$ 22.8°C) cluster with sample number $N = 290$; the weak WS, medium DP (WS $\leq$ 13 m s$^{-1}$, 22.8°C $<$ DP $\leq$ 24.1°C) cluster with sample number $N = 298$; the weak WS, high DP (WS $\leq$ 13 m s$^{-1}$, DP $>$ 24.1°C) cluster with sample number $N = 283$.

The scatter plots of lightning yield versus PM$_{10}$ for the three clusters are presented in Figure 4. Sample number $N$, regression coefficient $b$ of regression equation and correlation coefficient $R$ are presented in Figure 4 too. It shows that correlation coefficient $R$ is the highest for the weak WS, high DP cluster ($R = 0.232$), then for the weak WS, medium DP cluster ($R = 0.205$) and is the lowest for the weak WS, low DP cluster ($R = 0.200$). Significance level $p$ is below 0.001 for all of the three cluster. Regression coefficient $b$ is obvious higher in the weak WS, high DP cluster ($b = 117.0$) than those of the weak WS, low DP cluster ($b = 12.1$) and the weak WS, medium DP cluster ($b = 69.8$). These results suggest that high DP is favorable for lightning yield increasing when aerosols increase.

To study the AIV change in different aerosol concentration levels for the weak WS (WS $<$ 13 m s$^{-1}$) cluster, hourly lightning yield is calculated as a function of PM$_{10}$ for this cluster following the previous papers (Li et al., 2018; Rosenfeld et al., 2007). It is shown in Figure 5a that in general lightning yield increases with increasing PM$_{10}$. The increasing speed is slow when PM$_{10}$ increases from 0.01 to 0.035 mg m$^{-3}$, and is much faster when PM$_{10}$ varies from 0.035 to 0.1 mg m$^{-3}$, and is nearly zero when the value of PM$_{10}$ is above 0.1 mg m$^{-3}$.
Then, hourly lightning yield is calculated as a function of PM$_{10}$ for the three low weak WS clusters (WS $\leq$ 13 m s$^{-1}$, DP $\leq$ 22.8°C; WS $\leq$ 13 m s$^{-1}$, 22.8°C < DP $\leq$ 24.1°C; WS $\leq$ 13 m s$^{-1}$, DP $>24.1$°C). It is shown in Figure 5b that lightning yield increases with a slow speed when PM$_{10}$ is below 0.035–0.045 mg m$^{-3}$, thereafter, it increases with a faster speed for all of these three clusters. When the three clusters are compared with each other, it is found that the increasing speed is the fastest in the WS $\leq$ 13 m s$^{-1}$, DP $>24.1$°C cluster, then in the WS $\leq$ 13 m s$^{-1}$, 22.8°C < DP $\leq$ 24.1°C cluster, and is the slowest in the WS $\leq$ 13 m s$^{-1}$, DP $\leq$ 22.8°C cluster. These results suggest that the increasing speed is faster with higher DP.

Besides, for the WS $\leq$ 13 m s$^{-1}$, DP $\leq$ 22.8°C cluster, it is found that a reversal in the trend sign takes place when the value of PM$_{10}$ reaches 0.1 mg m$^{-3}$, that is, lightning yield increases with increasing PM$_{10}$ when PM$_{10}$ is below 0.1 mg m$^{-3}$, and decreases with increasing PM$_{10}$ when PM$_{10}$ is above 0.1 mg m$^{-3}$. It might suggest...
that PM$_{10}$ equal to 0.1 mg m$^{-3}$ is the optimal aerosol concentration ($N_{\text{op}}$) for this cluster. While for the WS $\leq 13$ m s$^{-1}$, $22.8^\circ$C $< \text{DP} \leq 24.1^\circ$C cluster, a $N_{\text{op}}$ is also found, and it is 0.105 mg m$^{-3}$ which is higher than that of the WS $\leq 13$ m s$^{-1}$, $\text{DP} \leq 22.8^\circ$C cluster ($\approx 0.1$ mg m$^{-3}$). However, no $N_{\text{op}}$ exists for the WS $\leq 13$ m s$^{-1}$, $\text{DP} > 24.1^\circ$C cluster. These results suggest that $N_{\text{op}}$ is higher with higher DP.

7 | DISCUSSION

It was found in this study that lightning yield increases with increasing PM$_{10}$ for the WS $\leq 13$ m s$^{-1}$ cluster, but not for the medium WS (13 m s$^{-1}$ $< \text{WS} \leq 26$ m s$^{-1}$) and the strong WS (WS $> 26$ m s$^{-1}$) clusters. The result suggests that aerosols enhance convective strength under the weak WS conditions rather than the strong WS conditions. The reason for the phenomenon is that the increase in condensational heating is larger than the increase in evaporative cooling when aerosols increase under the weak WS conditions, which has been pointed out by previous papers (Chen et al., 2015; Fan et al., 2009; Lee et al., 2008). However, these previous papers have also pointed out that aerosols should suppress convective strength when WS is strong, which has not been found in this study. The reason for this phenomenon is unknown and will be further studied in the future.

Warm cloud base is reported to be another favorable factor for AIV by many previous papers (e.g., Khain et al., 2008; Koren et al., 2014; Li et al., 2011). These papers have pointed out that aerosol effect could be very significant under the conditions of warm-cloud bases where the warm-cloud zone is deeper and the suppression of warm rain by aerosols is more significant and weak wind shear where convection is nearly vertical and the increase of latent heating dominates over the increase of evaporative cooling; on the contrary, in the cases where strong wind shear exists and/or cloud bases are cold, aerosols suppress convection due to strong evaporative cooling of the small cloud droplets and/or less efficient ice growing processes. In this study, the weak WS cases were grouped into three clusters by different DP to study the role of DP. It was found that AIV is the strongest for the weak WS, high DP (WS $\leq 13$ m s$^{-1}$, DP $> 24.1^\circ$C) cluster, then for the weak WS, medium DP (WS $\leq 13$ m s$^{-1}$, $22.8^\circ$C $< \text{DP} \leq 24.1^\circ$C) cluster, and is the least for the weak WS, low DP (WS $\leq 13$ m s$^{-1}$, $\text{DP} \leq 22.8^\circ$C) cluster. The result agrees with the results in the previous studies and is once again proof that high DP is favorable for AIV.

It was found by previous papers (Dagan et al., 2015; Fan et al., 2009; Jiang et al., 2010) that there is an optimal concentration $N_{\text{op}}$ for AIV in convective system, that is, when aerosol conditions are shifted from super pristine to $N_{\text{op}}$, the clouds formed are deeper; whereas for concentrations greater than $N_{\text{op}}$, increasing aerosols would lead to cloud suppression. The existence of $N_{\text{op}}$ results from two competing aerosol effects, that is, on the one hand, more aerosols delay the onset of collection processes and provide a larger droplet surface area for condensation, therefore, enhance the cloud’s development; while on the other hand, more aerosols result in a stronger drag force (driven by the larger mass) and stronger entrainment that suppresses the cloud’s development (Dagan et al., 2015). It was also found by these papers that $N_{\text{op}}$ is not the same for all cases, and they have discussed $N_{\text{op}}$ in the context of precipitation susceptibility (Jiang et al., 2010), sensitivity to WS (Fan et al., 2009) and different thermodynamic conditions (Dagan et al., 2015). By studying the change of AIV in different aerosol concentration levels in this study, it was found that $N_{\text{op}}$ exists when WS is low, and $N_{\text{op}}$ would be larger for higher DP. The result in this study is in line with the results in the previous papers, and might provide a tool (observational surface dew point temperature) to analyze the variation of $N_{\text{op}}$.

8 | CONCLUSION

By studying lightning and convective rainfall in Guilin, China using the data from July 2010 to December 2019, it was found that convective rainfall fluctuates less when compared with lightning in convective system. A hypothesis was put forward that the difference in fluctuations between convective rainfall and lightning is attributed to AIV. To test this hypothesis, lightning yield, which is defined as the ratio between lightning and rainfall, was analyzed. It was found that lightning yield has a positive correlation with PM$_{10}$ when WS is low and DP is high for convective precipitation, which is in line with the previous studies showing that AIV depends strongly on weak wind shear and/or warm cloud base (e.g., Chen et al., 2015; Fan et al., 2009; Khain et al., 2008; Koren et al., 2014; Li et al., 2011; Peng et al., 2016). This suggests that AIV exists in the study area, and suggests that the hypothesis is reasonable, and lightning yield can be used as a surrogate to study AIV.

For the purposes of this study, we chose only two environmental factors (WS and DP) with which to stratify the data. Both of these two parameters can provide significant information about the environment in which convective forms. However, it is impossible to entirely rule out the role of the environment, since other factors can be important too. For example, Storer et al. (2014) and Singh et al. (2014) have proved that AIV can be very
different under various CAPE conditions. Khain et al. (2008) and Lee (2011) have found that humidity is a factor in determining AIV. Studying other factors such as these is important work and will be useful in future study.

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CONFLICT OF INTEREST
The authors declare no potential conflict of interest.

AUTHOR CONTRIBUTIONS
Xiong Li: Conceptualization; data curation; formal analysis; investigation; methodology; project administration; resources; software; supervision; validation; visualization; writing – original draft; writing – review and editing.
Ying Pan: Conceptualization; formal analysis; writing – review and editing.
Zhaoyu Mo: Formal analysis.
Risheng Liu: Formal analysis.

ORCID
Xiong Li https://orcid.org/0000-0001-6817-0178

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