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RESEARCH ARTICLE

# Influence of aerosols on lightning activities in central eastern parts of China

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## Abstract

Time series data of lightning flash rates, aerosol optical depth (AOD), surface relative humidity, potential temperature, and convective available potential energy (CAPE) for 14 consecutive summers (2001–2014) over central eastern parts of China (32.5°–40°N, 100°–120°E) have been analyzed to investigate the impact of aerosol on the lightning flash rate. The Pearson correlation and the partial correlation are used to study the linear correlations between the lightning flash rate and AOD, potential temperature, surface relative humidity, and CAPE. The results show that the lightning flash rate is positively correlated ($r$ = .64) with AOD under relatively clean conditions (AOD < 1.0), which may result from aerosol microphysical effect. In the situation of high aerosol concentration (AOD > 1.0), the correlation between AOD and lightning flash rate is not obvious ($r$ = −.06), which may be due to the radiation effect of aerosol and the decrease of the number of large ice particles caused by excessive aerosol concentration. CAPE and surface relative humidity are both positively correlated with the lightning flash rates under relatively clean (AOD < 1.0) and relatively polluted (AOD > 1.0) conditions. Potential temperature is moderate positively correlated with the lightning flash rate under relatively clean conditions ($r$ = .51, AOD < 1.0) but shows no significant linear relationship under relatively polluted conditions ($r$ = .07, AOD > 1.0).

KEYWORDS

aerosol, cloud microphysics, correlation coefficient, lightning activity

## 1 | INTRODUCTION

Lightning is a strong discharge phenomenon in the atmosphere, which is often accompanied by serve weather such as heavy precipitation, hail, tornado, and so on. Lightning is also one of the important sources of nitrogen oxides in the atmosphere, and thus the occurrence of lightning has a significant influence on global atmospheric chemistry (Schumann and Huntrieser, 2007; Murray, 2016; Tost, 2017). In addition, the cloud to ground (CG) lightning can cause forest fires, hit people and human facilities, causing properties damage, and casualties (Flannigan and Wotton, 1991; Krause et al., 2014; Raga et al., 2014; Abdollahi et al., 2019; Holle et al., 2019). Therefore, research on the response of lightning to various meteorological factors and climate change remains an important research topic (Reeve and Toumi, 1999; Xiong et al., 2006; Romps et al., 2014; Kotroni and Lagouvardos, 2016; Dewan et al., 2018; Finney et al., 2018). Aerosol, because of its interaction with clouds, also has an important impact on lightning activity, coupled with the contribution of human activities to aerosol, so it is meaningful to study the influence of aerosol on lightning in different regions (Williams, 2005; Thornton et al., 2017; Li et al., 2017b).

The influence of aerosols on the process of generating lightning is complicated. Aerosol could influence lightning activity through modification of cloud microphysics. Over the past years, much has been learned regarding the interaction between aerosols and clouds. Numerous studies using parameterized models and remote sensing observation have shown that greater concentrations of aerosols result in the production of more small cloud droplets and reduced collision efficiencies, which can delay the formation of raindrops (Nakajima et al., 2001; Feingold, 2003; Khain et al., 2005; Rosenfeld et al., 2008). The increase in the number concentration of cloud condensation nuclei (CCN) can also result in an increase of ice particles (Khain et al., 2005). At extremely high concentration condition, ice production is inhibited because of inefficient ice nucleation and less latent heat released (Li et al., 2008). Meanwhile, charge separation between rebounding collisions between ice particles in the presence of supercooled droplets is widely referred as the primary electrification processes in thunderstorms via laboratory studies (Takahashi, 1978; Jayaratne et al., 1983; Saunders et al., 1991). Therefore, aerosol microphysical effect has a vital influence on lightning activity.

In recent years, considerable progress has been made in understanding the interactions between aerosols and lightning activities. For instance, forest fires are known to produce aerosol particles that are dispersed into the troposphere, allowing an investigation of the response of lightning activities to aerosols. The findings indicate that regions of enhanced percentage of positive CG lightning are filled with smoke aerosols originating from forest fires (Latham, 1991; Lyons, 1998; Murray et al., 2000; Lang and Rutledge, 2006). The contrast in lightning activities over land and ocean can attributed to the difference in thermodynamic, convection, and aerosol concentration over land and ocean (Füllekrug et al., 2002; Williams and Stanfill, 2002; Yuan et al., 2011). In addition, many studies have been conducted to investigate the influences of urban effects on lightning activity. Both the urban heat island effect and air pollution over urban regions can cause an enhancement in lightning activities (Naccarato et al., 2003; Kar et al., 2007), which can be examined in relation to the PM10 (particulate matter of less than 10 μm in diameter) and $SO_2$ concentrations (Steiger and Orville, 2003; Kar et al., 2009; Farias et al., 2014). Yuan et al. (2011) examined lightning data from the lightning-imaging sensor (LIS) on board the Tropical Rainfall Measuring Mission (TRMM) satellite and MODIS AOD (aerosol optical depth). They further estimated that a 60% increase in aerosol loading leads to a >150% increase in the lightning flash rate. The pioneering work by Tan et al. (2016) revealed that aerosol radiative effects may be one of the main reasons for the decrease of the lightning flash density in a long period by analyzing lightning data, AOD, surface temperature and convective available potential energy (CAPE) during summer. This can be explained in terms of how aerosols affect the solar radiation through scattering, absorption, and reflection and thus cool the surface and heat the atmospheric layer (Cheng et al., 2007; Wen et al., 2007, 2008; Siingh et al., 2013, 2014). The latent heat flux is thus reduced, the atmosphere becomes more stable and the occurrence of thunderstorms is suppressed (Kaufman et al., 2002; Koren et al., 2004, 2008; Li et al., 2017a). Similarly, recent results presented by Wang et al. (2018) and Lal et al. (2018) indicated that the lightning density increases significantly with AOD under relatively low aerosol concentration conditions, while lightning activity is inhibited when the aerosol concentration is relatively high.

The discussions above suggest that aerosols have a profound influence on electrification and lightning discharges in thunderclouds, and due to the complexity of the mechanism through which aerosols affect lightning activity, the possible effects of aerosol on thunderstorm electrification should be further studied. In this work, we perform a data analysis in central and eastern parts of China (32.5°–40°N, 100°–120°E) to elucidate the relationship between aerosol and lightning activity.

## 2 | DATA AND METHOD

Lightning, AOD and meteorological parameters data from 2001 to 2014 are used in this study. The lightning data from 2001 to 2014 is retrieved from the low resolution monthly time series (LRMTS) dataset which is gridded lightning climatology dataset that provides the monthly flash rate at a 2.5° × 2.5° spatial resolution. The LRMTS is a merger of two lightning data which are detected by LIS aboard the TRMM satellite and optical transient detector (OTD) on the OV-1 satellite (Cecil et al., 2014). The LRMTS has been processed with a 3-month moving average to smoothing the lighting data. Compared with the traditional ground lightning detection data, the lightning data detected by LIS and OTD based on satellite can easily show the spatial distribution characteristics of lightning on a large scale and contains cloud-to-ground discharges, intracloud, and cloud-to-cloud discharges during day and night (Christian et al., 1999).

Monthly average AOD data is considered from MODIS-Terra Ver.6.1 Level 3 with grid resolution 1° × 1°. The AOD at 550 nm is retrieved using the deep-blue-dark-target combined algorithm. Convective available potential energy (surface based CAPE), potential temperature (Wang et al., 2018), and surface relative humidity are chosen as meteorological parameters. Potential temperature ($\theta$: in units of K) is calculated by:

$$\theta = T\left(\frac{1000}{P}\right)^{0.286}$$

$T$ (in units of K) represents the 2-m temperature and $P$ (in units of hPa) represents pressure. CAPE, 2-m temperature, sea level pressure, and surface relative humidity data with grid resolution 2.5° × 2.5° are obtained from the European Centre for Medium-Range Weather Forecast (ECMWF) ERA-Interim reanalysis monthly mean product.

AOD data are resampled onto 2.5° × 2.5° resolution grids, which is consistent with lightning and meteorological parameters data. AOD and meteorological data (potential temperature, surface relative, and CAPE) are all processed with a 3-month moving average. The strength of the linear relationship between the lightning density and other data (AOD, CAPE, potential temperature, and surface relative humidity) are characterized by Pearson and partial correlation coefficients (Pearson, 1896).

Region of interest (32.5°–40°N, 100°–120°E) in this study is shown in Figure 1 where is enclosed by the black square. The east part of the region is heavily polluted

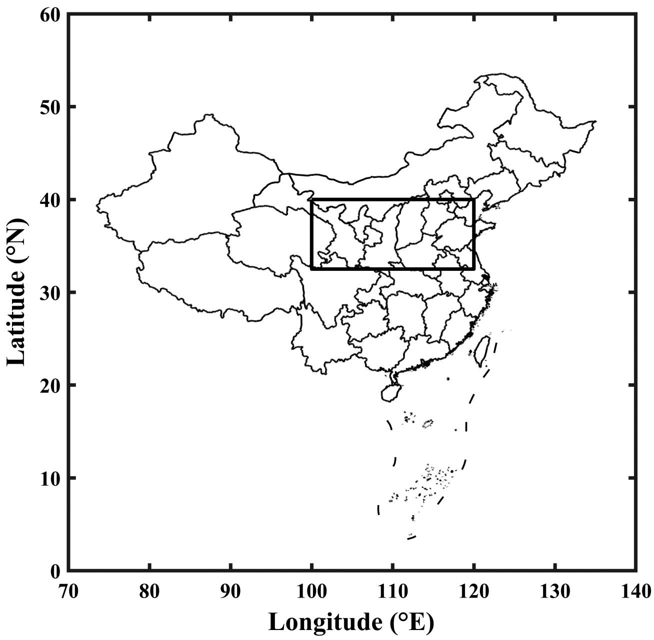


**FIGURE 1** Map of China and the region of interest in this study (32.5°–40°N, 100°–120°E) is outlined by black rectangle

because eastern cities are more developed and produce more pollutants, while the west part of the region is relatively clean. Therefore, a comparative study can be performed between the east and west parts of this region. Additionally, it has been suggested that monsoons at low latitudes (such as southern China) have a significant impact on lightning activities (Yuan and Qie, 2008). In order to exclude interference factor (monsoon), the region in this work is employed.

## 3 | RESULTS

Figure 2a shows the topographic map and wind field map of the study region. The spatial distribution of summer mean AOD and lightning flash rates for period 2001–2014 are depicted in Figure 2b,c, respectively. It can be found that the terrain of the study area is generally high in the west and low in the east. The east part is located in the plain by the sea, while the west part is mostly in the plateau. From Figure 2b, it can be found that the mean value of AOD in the western half (32.5°–40°N, 100°–110°E) is below 0.5, while the mean value of AOD in the eastern half (32.5°–40°N, 110°–120°E) is generally higher than 1.0. The presence of a large number of cities and intensive human activities in the eastern plain region leads to the emission of a large number of air pollutants, resulting in higher concentrations of particulate matter over the eastern area. The blocking of air pollutants in the western mountains of the eastern plains and the weak human activities in the west have resulted in lower aerosol concentrations in the western regions. It is worth noting that a similar distribution is found for lightning flash rates (as seen Figure 2c). The average lightning flash rate in the western region is less than 0.03 $km^{-2}d^{-1}$, compared with 0.05 flashes $km^{-2}d^{-1}$ in the eastern region. Aerosols could potentially be one of the reasons for the distribution of lightning over these areas. However, lightning activity can also be affected by many other meteorological factors like CAPE, temperature, relative humidity (Williams, 1994; Xiong et al., 2006; Bang and Zipser, 2016), and so on. Figure 3 shows the variation of lightning flash rates and other factors (AOD, CAPE, Potential temperature, and surface relative humidity) with longitude. The variation of aerosol and lightning flash rates with longitude is consistent (as seen Figure 3a). It can be found that the potential temperature and surface humidity are both high in eastern part of the study region, as well as high value of CAPE (as seen in Figure 3b–d), which is prone to the formation of convection and lightning activities. On the contrary, these parameters in the western region are relative small. Therefore, the spatial distribution of lightning activity in the study area is not only caused by aerosols, and other factors (CAPE, potential temperature, and surface relative humidity) also have a great influence.

In order to further investigate the impact of aerosol on lightning activity in the region of interest, a scatterplot and a cubic fitting curve of AOD and lightning flash rates are presented in Figure 4. The cubic fitting curve shows lightning flash rates first increase with increasing AOD and then decrease when AOD exceeds the turning point around AOD = 1.1. It can also be seen from the scatterplot that data points become more scattered as AOD increases. In the case of relatively low aerosol concentration, aerosol seems to promote lightning activities, but in the case of high aerosol concentration, the relationship between lightning flash rates and AOD is not clear. In order to study the response of lightning activity to AOD and other factors (CAPE, potential temperature, and surface relative humidity) under different pollution conditions, the analysis of correlation coefficient has been carried out in the following content.

All data points are divided into two groups according to AOD greater or less than the turning point value. According to the results of Figure 4, the relationship between aerosols and lightning flash rates in relatively low aerosol concentration conditions is quite different from that in relative high aerosol concentration conditions. The dividing point between high and low aerosols concentration is the inflection point (about AOD = 1.1) of fitting curve with reference to Figure 4. However, in

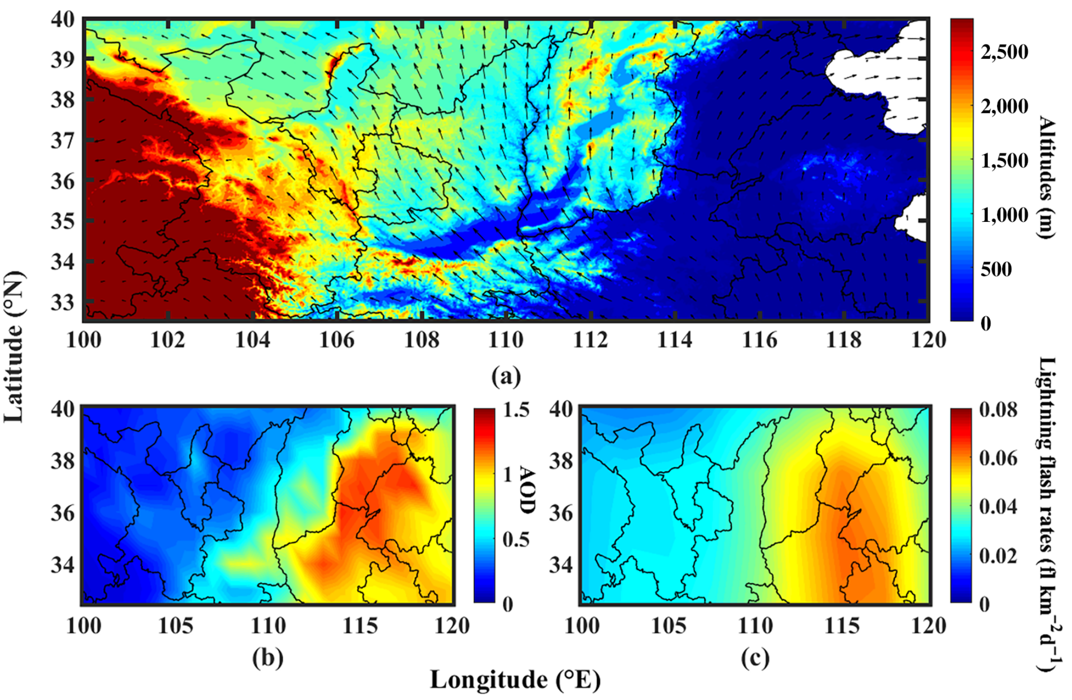


**FIGURE 2** The contour and wind field (850 hPa) map of the study area (a). The mean wind field data of 850 hPa is obtained from the ERA-Iterim reanalysis with a spatial resolution of 0.5° × 0.5°. Spatial distribution of (b) aerosol optical depth (AOD) at 550 nm derived from the MODIS at a spatial resolution of 1° × 1°and (c) lightning flash rate derived from LIS at a spatial resolution of 2.5° × 2.5°for the period 2001–2014 including (June, July, and August). Both AOD and lightning data have been smoothed with a roughly 3-month moving average and then the 3 months (June, July, and August) mean are calculated to represent the value of AOD and lightning flash rates in summer

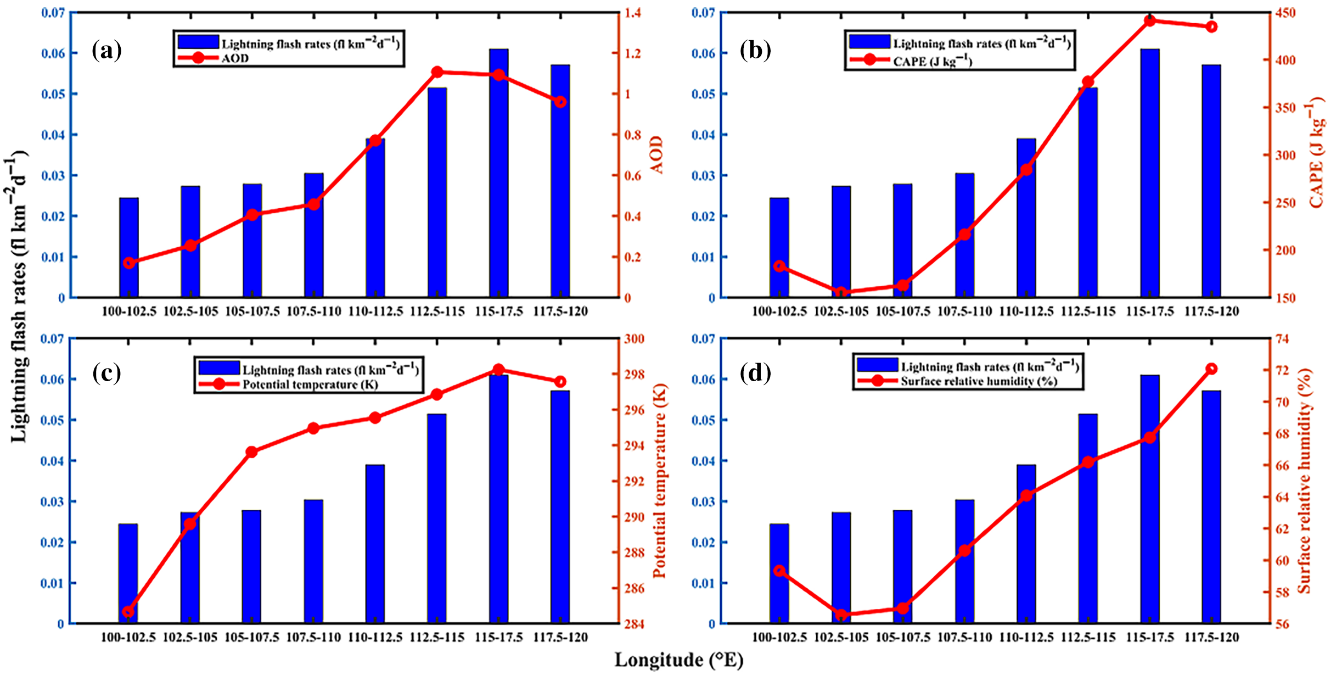


**FIGURE 3** Longitudinal variation of mean AOD (red line) and lightning flash rate (blue) from June to August during the period 2001–2014. Sub graphs (b–d) are same as (a), but for lightning flash rates and CAPE, potential temperature, surface relative humidity. AOD and lightning data are processed with 3-month moving average and then the 3 months (June, July, and August) mean are calculated to represent the value of AOD and lightning flash rates in summer per year

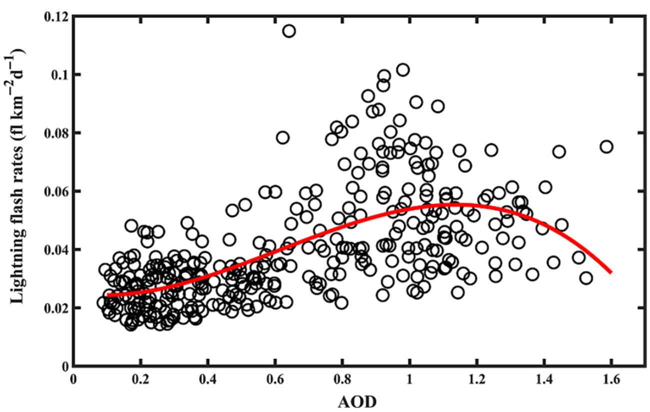


**FIGURE 4** Scatter plots and cubic fitting curve between lightning flash rate and AOD in June, July, and August from 2001 to 2014. All data are processed with the same method of Figure 3

order to ensure enough data in each group, the value of AOD = 1.0 is eventually selected as the location of turning point. The correlations between aerosol-lightning flash rates, surface relative humidity-lightning flash rates, potential temperature-lightning flash rates, and CAPE-lightning flash rates are analyzed under low aerosol concentration (AOD < 1.0) and high aerosol concentration (AOD > 1.0), respectively. The results of the Pearson correlation coefficient are shown in Figure 5.

The AOD is positively correlated ($r$ = .64) with the lightning flash rates under low aerosol concentration, while a weak correlation ($r$ = −.06) is found under high aerosol concentration. This indicates that the effect of the aerosol on the lightning activity is different for different aerosol concentrations. Figure 5b,f shows that CAPE correlates well with lightning flash rates under both low aerosol concentration ($r$ = .72) and high aerosol concentration ($r$ = .68). The partial correlation analyses between the lightning flash rates and two factors (AOD and CAPE) are then applied to analysis the independent relationship between the aerosol and lightning flash rates. It can be found that the partial correlation between AOD and lightning flash rates are both weak ($r$ < .3) under relatively clean conditions and polluted conditions, while the connection between CAPE and lightning flash rates is stronger ($r$ > .5). This suggests that the effects of aerosol on lightning activity may be indirect which is consisted with the result found in Africa (Wang et al., 2018). The high, positive correlations between CAPE and lightning activity in this study indicate that CAPE seems to play a vital role in the occurrence of summer lightning activity in study area. CAPE represents the potential buoyancy of idealized rising air parcel and thus is a measure of the instability of atmosphere. The relationship between CAPE and lightning activity has been found in

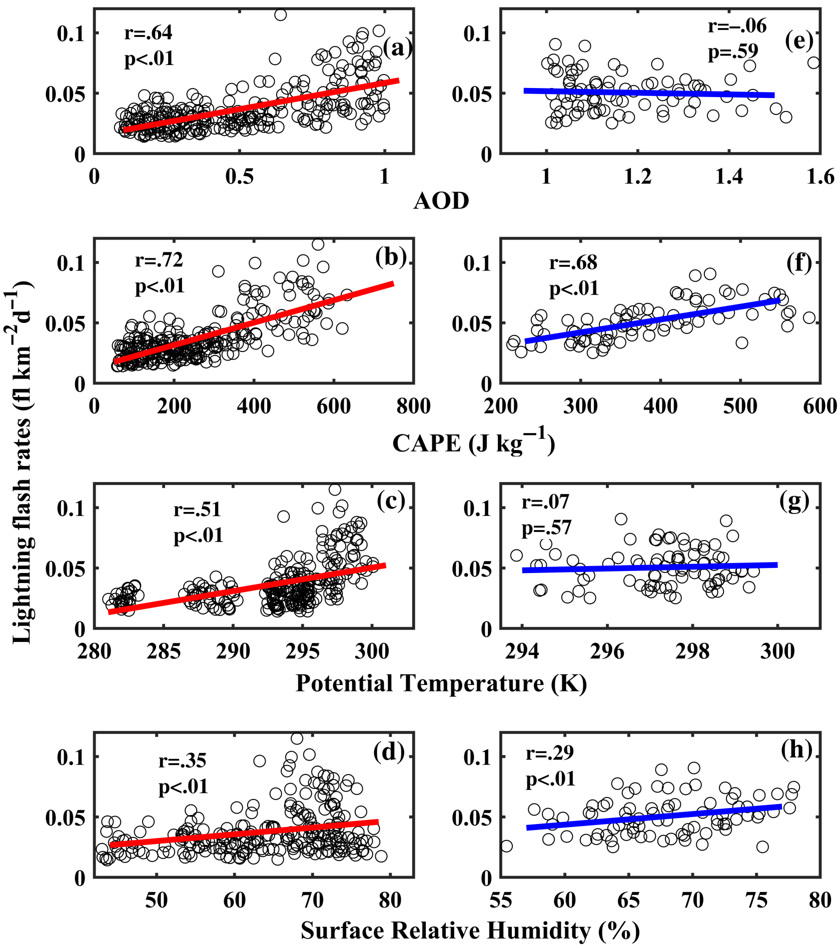


**FIGURE 5** Scatter plots of monthly mean lightning flash rate with AOD, surface relative humidity, CAPE, and potential temperature for the study area. Values of correlation coefficients and significance level are also given in each panel. The Panels (a–d) show the correlation coefficient between lightning flash rate and each factor (AOD, surface relative humidity, CAPE, and potential temperature) in the case of low aerosol concentration (AOD < 1.0) and the remaining Panels (e–h) are conducted in the situation of high aerosol concentration (AOD > 1.0). All data are processed with the same method of Figure 3

many other regions over the world such as India, Southeast Asia, and Bangladesh (Murugavel et al., 2012; Pawar et al., 2012; Siingh et al., 2013; Murugavel et al., 2014; Dewan et al., 2018). Pawar et al. (2012) studied the relationship between CAPE and lightning activity over central India during summer monsoons. Their results show a significant increase in lightning activity over central India during 1998–2009 which is attributed to an increase in CAPE. The aerosol concentration has no significant effect on the relationship between CAPE and lightning activity in this study.

A moderate, positive correlation ($r = .51$, $p < .01$) between lightning flash rates and potential temperature is found under relatively low aerosol concentration conditions (Figure 5c), but no significant correlation ($r = .07$, $p = .57$) between them can be found under high aerosol concentration conditions. The rising surface temperature caused by the heating from solar radiation will increase the instability of boundary layer, which helps the formation of convection and lightning. However, under relatively polluted conditions, high aerosol concentrations can warm the atmosphere by absorbing incoming solar radiation and therefore cool the surface by reflecting solar radiation. Thus the atmosphere becomes more stable and is not conducive to the formation of lightning. The relationship between temperature and lightning activity may be more complicated under relatively high aerosol concentration.

As shown in Figure 5d,h, the correlation between surface relative humidity and lightning flash rates is weak, positive both in the situation of low ($r = .35$) and high aerosol concentrations ($r = .29$). This indicates that the effect of surface relative humidity on lightning activity does not change much under relatively clean or polluted conditions. The formation of thunderstorm requires sufficient water vapor which plays an important role in the formation of hydrometer particles. The increase of relative humidity will lead to the enhancement of the convection and lightning activity (Shi et al., 2018). It is worth noting that the lightning flash rates seem to decrease with the increase of surface relative humidity after the surface relative humidity is greater than around 74%. This result is consistent with the study of Xiong et al. (2006) which found that lightning activities response to surface relative humidity with a watershed of about 72–74%. Excessive relative humidity on the ground absorbs solar radiation through evaporation, reducing the ability of convection to rise, thus inhibiting the occurrence of lightning activities.

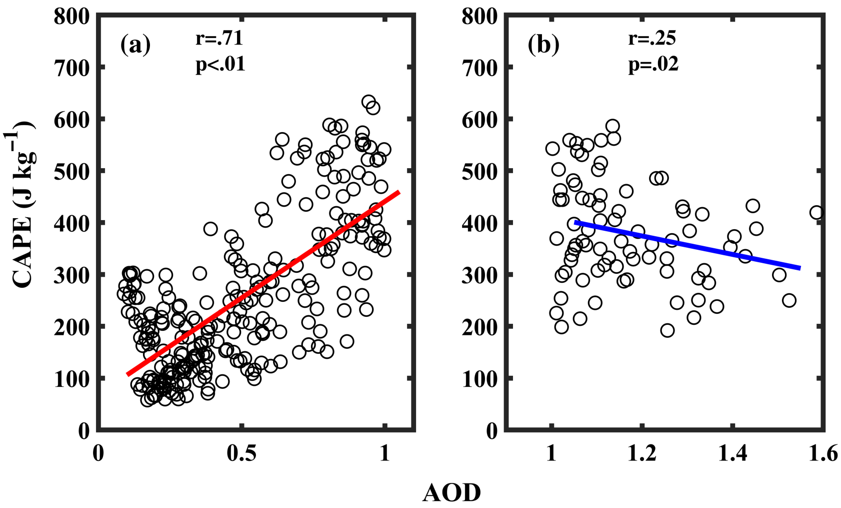


**FIGURE 6** Scatter plots of monthly mean AOD with CAPE for the study area. Values of correlation coefficients and significance level are also given in each panel. The panels (a) and (b) show the correlation coefficient of AOD and CAPE in low (AOD < 1.0) and high (AOD > 1.0) aerosol concentration, respectively. All data are processed with the same method of Figure 3

In addition, a strong positive correlation ($r$ = .71, Figure 6a) can be found between AOD and CAPE under relatively clean conditions and a weak negative correlation ($r$ = −.25, Figure 6b) can be found between AOD and CAPE under relatively polluted conditions. This suggests that aerosol microphysics effects might play the key role in low aerosol concentration. More aerosols acting as CCN leads to smaller cloud droplets, thus delaying the process of warm rain, which allows more liquid water to reach the mixed phase cloud region and releases more latent heat to change environmental variables like CAPE to make atmosphere more unstable. The negative relationship between AOD and CAPE under relatively polluted conditions suggests that the aerosol radiative effects may play a dominant role. Excessive aerosol can reduce the instability of atmosphere through changing the radiation budget (Li et al., 2017b).

## 4 | CONCLUSION AND DISCUSSIONS

Influence of aerosols on lightning over central eastern parts of China (32.5°–40°N, 100°–120°E) for summer season, that is, June, July, and August, has been analyzed utilizing AOD, lightning, surface humidity, potential temperature, and CAPE data from the MODIS, LIS, and ECMWF ERA-Interim reanalysis. The results show that the relationship between lightning activity and aerosol is obviously different under different aerosol loadings. In the case of relatively low aerosol concentration (AOD < 1.0), there is a positive correlation between lightning flash rate and AOD, which may due to aerosol microphysical effect. No significant linear relationship can be found under high aerosol concentration (AOD > 1.0). This may due to the fact that aerosol radiative effect counteracts with aerosol microphysical effect. The CAPE is strong, positively correlated with the lightning flash rate under both relatively clean (AOD < 1.0) and polluted (AOD > 1.0) conditions. The surface relative humidity is also positively correlated with the lightning flash rate but the correlation coefficients are not high ($r$ = .35 under relatively clean conditions and $r$ = .29 under relatively polluted conditions). The relationship between potential temperature and lightning flash rate varies greatly with aerosol concentrations: $r$ = .51 under relatively clean conditions and $r$ = .07 under relatively polluted conditions. The weak connection between the potential temperature and the lightning flash rate under relatively polluted conditions may be attributed to the participation of aerosol radiative effects. In addition, a strong, positive correlation between the AOD and the CAPE ($r$ = .71) is found under low aerosol concentration conditions and a weak negative correlation ($r$ = −.25) is found under relatively polluted conditions. This further indicates that aerosols seem to play different roles under high (AOD > 1.0) and low (AOD < 1.0) aerosol concentrations.

In addition, excessive aerosol concentration in the thunderstorms will induce the decrease of large-sized ice particles and thus suppresses the process of thunderstorm cloud electrification. This may be another explanation of the weak connection between lightning activity and aerosol under relatively high aerosol concentration in this study. At present, a host of studies have revealed that the increase of aerosol concentration leads to the increase of the cloud droplets concentration (Nakajima et al., 2001; Wang, 2005; Yang et al., 2011). Therefore, cloud droplets become smaller with fixed liquid water content. Smaller cloud droplets are not conducive to the formation of raindrops, so that more cloud droplets will pass into the super cooling zone of the cloud through updraft flow and freeze to release more latent heat, which stimulates the development of convection and creates more ice crystals (Andreae et al., 2004; Khain, 2009; Xiao et al., 2014). Thereafter, more large-sized ice particles (such as graupel and hail) will be produced through the microphysics development of ice crystals. It suggests that the electrification process in thunderstorm clouds is mainly caused by the collision and separation between ice crystals and graupel (Takahashi, 1978; Saunders et al., 1991; Helsdon et al., 2001). Therefore, the larger concentration of aerosol leads to higher ice particles content, leading stronger electrification process. However, when the concentration at very high level, more small size of ice crystal perhaps suppress the formation and development of graupel or hail. The main cause may be the profound water competition, and then the cloud water collection rate of ice particles may be weak. In this situation, weak electrification in thunderclouds with less large size ice particles may be associated with weak lightning activities.

Furthermore, the mechanism of aerosol affecting lightning activity is complex. In the future works, it is worth investigating the effect of aerosols on lightning discharge process by a model study. Meanwhile, some other factors like the effect of urban or the difference between the continent and ocean are worth considering in further studies.

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