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(Research Article)

Aerosol-Cloud-Lightning Interactions: A Comparative Study of Mountainous and Coastal Environments in Iran

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Abstract

Aerosols affect cloud microphysical processes and lightning activity by acting as cloud condensation nuclei. To investigate this, we analyzed lightning density data from the Lightning Imaging Sensor (LIS), alongside cloud fraction, cloud-top height, ice cloud optical thickness, and Aerosol Optical Depth (AOD) data from MODIS, as well as Convective Available Potential Energy (CAPE) from ERA5 data for the period 2000-2014. The study focused on two distinct environmental areas (R1 and R2) in Iran: R1, located between 32.5°N-34°N and 46°E-48°E in the mountainous west of Iran, experiencing three distinct climates–Mediterranean, cold mountainous, and warm semi-desert. In contrast, R2, situated between 27.5°N-29°N and 50°E-52°E, is characterized by plains with a warm and dry climate in the north and a humid, warm climate in the south. Monthly variation analysis revealed that lightning activity and AOD correlate well in spring and autumn but diverge in winter, with a negative correlation in summer due to suppressed convective storms at high AOD levels. Annual variation analysis indicates higher electrical activity in R1, which frequently experiences sand and dust storms. The results showed a moderate positive correlation between AOD and lightning activity in both regions, attributed to various AOD sources such as black carbon, dust, sea salt, and sulphate. Cloud fraction, ice cloud optical thickness, and cloud-top height showed positive correlations with lightning density in both R1 and R2 However, the correlation between CAPE and lightning density was lower in R2, likely due to higher atmospheric humidity stabilizing the environment and reducing the frequency and intensity of thunderstorms.

Keywords: Aerosols, Lightning, AOD, Cloud properties, CAPE.

1. Introduction

During thunderstorms, many solid aerosol particles are lifted from the ground, significantly altering cloud microphysical processes. These particles are released into thundercloud, where they act as cloud condensation nuclei (CCN). An increase in aerosol concentration can delay convection and the onset of precipitation while reducing the size of cloud ice particles (Khain et al., 2005). Such changes in cloud microphysics can delay cloud glaciation, leading to colder cloud temperatures and, consequently, an increase in lightning flashes (Yoshida et al., 2009; Yuan et al., 2011).

Several studies have explored the relationship between aerosols and lightning, with many reporting a positive correlation between aerosol concentrations and lightning frequency (e.g. Westcott, 1995; Lyons et al., 1998; Fernandes et al., 2006; Altaratz et al., 2010; Lal and Pawar, 2011; Wang et al., 2011; Altaratz et al., 2017; Shi et al., 2020; Liu et al., 2021; Wang et al., 2021; Chakraborty et al., 2021; Shubri et al., 2024). This observational evidence suggests that aerosols can significantly influence lightning activity, potentially altering the frequency, intensity, and distribution of lightning strikes by changing the electrical properties of clouds and the atmospheric electrical environment.

The relationship between aerosols and lightning has been a topic of great interest in recent decades. Westcott (1995) was the first to establish the link between aerosols and lightning flash density. Their research showed that lightning activity increases in large cities and their downstream regions due to anthropogenic aerosol emissions. Lyons et al. (1998) further explored this relationship by examining the impact of wildfire smoke on

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cloud-to-ground lightning from April to June 1998. Originating from southern Mexico, the smoke was transported northward into the southern plains of the United States. Their findings revealed that smoke significantly influences lightning intensity, increasing both the percentage and maximum current of positively charged cloud-to-ground lightning. In subsequent studies, Fernandes et al. (2006) and Altaratz et al. (2010) conducted similar studies and discovered that higher concentrations of smoke lead to enhanced electrical activity. Lal and Pawar (2011) utilized satellite data from the Moderate Resolution Imaging Spectroradiometer (MODIS) and the Tropical Rainfall Measuring Mission (TRMM) to investigate the relationship between lightning activity and Aerosol Optical Depth (AOD) in four major Indian cities. Their findings indicated that lightning intensity increases due to the combined effects of cloud thermodynamics and aerosol concentrations in urban areas; however, the impact of aerosols on lightning is not noticeable in coastal cities. Wang et al. (2011) identified a positive correlation between lightning activity and aerosol loading in the Pearl River Delta region.

Furthermore, recent studies have developed our understanding of the link between aerosols and lightning. Farias et al. (2014) and Kar and Liou (2014) have revealed a positive correlation between cloud-to-ground lightning activity and the concentration of PM10 and SO2 in São Paulo and Taiwan. Tan et al. (2016) found that the rate of lightning flash density decreases during a long period due to aerosol radiative effects. However, the microphysical effects of aerosols may play a significant role in enhancing the rate of cloud-to-ground lightning. This highlights the complex interaction between aerosols, clouds, and thunderstorms, and highlights the necessity for researches into this issue.

According to Wang et al. (2018) and Lal et al. (2018), the relationship between lightning and AOD is dependent on AOD values. Gharaylou et al. (2020, 2024) used ground-based lightning data from the World Wide Lightning Location Network (WWLLN) and found a positive relationship between PM10 concentration, ground-level ozone concentration, and the number of lightning flashes in Tehran. Chowdhuri et al. (2020) observed that a reduction in surface pollution concentrations significantly impacts lightning activity in Kolkata. Gautam et al. (2021) further investigated the aerosol-lightning relationship in southern India from 2017 to 2020, concluding that an increase in AOD concentration is associated with an increase in the number of lightning flashes. In a more recent study, Dayeh et al. (2021) investigated the impact of aerosols on lightning activity in the Arabian Peninsula, revealing a positive linear relationship between AOD and lightning activity. They found that under low AOD conditions, the relationship is linear, with air-cloud interactions being the primary factor influencing lightning activity in relatively clean environments. Under higher AOD values, both aerosol-cloud and aerosol-radiation interactions, which depend on AOD properties such as type and size, may inhibit convection and lightning activity. Dayeh et al. (2021) also found that the linear relationship between AOD and lightning is considerably stronger in mountainous regions compared to other areas.

Lightning activity is also influenced by thermodynamic factors and cloud characteristics, including Convective Available Potential Energy (CAPE) (e.g., Rosenfeld et al., 2012; Proestakis et al., 2016; Zhao et al., 2020; Wang et al., 2021; Rafati and Fattahi, 2022), as well as cloud properties like cloud fraction, cloud-top height, and ice cloud optical thickness (e.g., Ushio et al., 2001; Zhao et al., 2017; Han et al., 2021). These factors can either enhance or suppress the conditions necessary for lightning formation by affecting the distribution and intensity of electric charges within clouds.

Due to the complex interactions between aerosols, lightning activity, and cloud microphysics, the possible effects of aerosols on thunderstorms need to be further studied. This study investigates the influence of aerosols, cloud properties, and CAPE on lightning activity in western Iran, a region with relatively high lightning activity, averaging 6-10 flashes per square kilometer annually from 1998 to 2015 (Cecil et al., 2014). We also examine the relationship between lightning flash density, cloud characteristics (including cloud fraction, cloud-top height, and ice cloud optical thickness), and CAPE during the period 2000-2014.

2. Data description and methodology

2-1. Data

Monthly data for cloud fraction, cloud-top height, ice cloud optical thickness, and AOD at 550 nm from level 3 of MODIS (MYD08_D3; http://modis-atmos.gsfc.nasa.gov) with a horizontal resolution of 1°×1 ° for the period 2000 to 2014 are used. The accuracy of MODIS AOD data is acceptable in most areas with available observations, with an average error of 15% (Kaufman et al., 2005; Mi et al., 2007; Levy et al., 2007). Moreover, both intracloud (IC) and cloud-to-ground (CG) lightning data from the lightning imaging sensor (LIS) and the optical transient detector (OTD) (https://ghrc.nsstc.nasa.gov/lightning/data/) were utilized. The LIS on the Tropical Rainfall Measuring Mission (TRMM) satellite detects optical emissions from lightning and operated for 17 years until 2015, providing global lightning data within ±38° latitude. The LIS/OTD combined product has been previously validated and documented by Cecil et al. (2014), with LIS detection efficiencies of 73% during daytime and 93% at night (Cecil et al., 2014)., Serving as a crucial indicator of atmospheric stability and convective storms, CAPE is defined as the vertical integration of buoyancy from the level of free convection (LFC) to the equilibrium level (EL) (Doswell III and Rasmussen, 1994; Tsonevsky et al., 2018). In this study, CAPE data were obtained from the ERA5 reanalysis for the period 2000-2014. ERA5, the fifth generation of global atmospheric reanalysis produced by the European Centre for Medium-Range Weather Forecasts (ECMWF) (Hersbach et al., 2020), provides hourly estimates of numerous atmospheric, land, and oceanic climate variables at a spatial resolution of 0.25° degrees. This advanced version of ERA-Interim now includes data from 1950 to the present (Bell et al., 2021).

The AOD data for different aerosol types–black carbon (BC), mineral dust, sea salt, and sulphate–were extracted from the MACC-II (Monitoring Atmospheric Composition and Climate Interim Implementation) reanalysis dataset, produced by ECMWF for the period 2003-2012. The MACC-II data have a horizontal resolution of 1° in both longitude and latitude, with a temporal resolution of 6 hours.

2-2. Study area

Figure 1 shows the topographic map of the study area. The research area is divided into two regions with distinct geographical and climatic conditions, referred to as R1 and R2. R1, located between 32.5°N-34°N and 46°E-48°E in western Iran is a mountainous region influenced by deserts to its west and south. It experiences three distinct climates: Mediterranean (moderate), cold mountainous, and warm semi-desert. R2, situated between 27.5°N-29°N and 50°E-52°E, is a plain region with varying climates–warm and dry in the north, and humid and warm in the south, characterized by intense evaporation due to long summer seasons (Pegahfar, 2022). These regions were selected due to their relatively high frequency of thunderstorms and lightning (Ghalhari and Shakeri, 2015). As well as their diverse climates, which allow for an investigation of aerosol impacts on lightning under different environmental conditions.

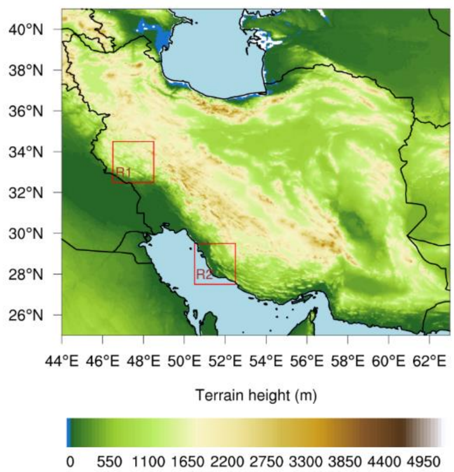


Figure 1. The topographic map (meters) of the study area. Red rectangles show the geographic locations of the studied regions.

2-3. Methods

We first identified days with lightning activity from January 2000 to December 2014, defined as days with at least one lightning strike within a 24-hour period. The LIS orbit passing over both study regions were tracked in 1° grids, and the number of flashes per pixel during each orbit passage was computed. The average AOD values during these lightning-active days were then extracted from the MYD08_D3 product for R1 and R2, following a similar approach to Dayeh et al. (2021). We analyzed the relationships between AOD, cloud properties, CAPE, and lightning flash density using Pearson correlation coefficient. This coefficient measures the strength and direction of the linear relationship between variables, ranging from -1 (negative correlation) to 1 (positive correlation), with 0 indicating no correlation. According to Mindrila and Balentyne (2017), a correlation coefficient below 0.3 signifies a weak positive relationship, 0.3-0.7 indicates a moderate positive relationship, and above 0.7 denotes a strong positive relationship, even if the scatterplot appears dispersed. Additionally, a p-value less than 0.01 or 0.05 indicates statistical significance at the 99% and 95% confidence levels, respectively (Mindrila and Balentyne, 2017). The four seasons are considered as winter (December–January–February, DJF), spring (March–April–May, MAM), summer (June–July–August, JJA), and autumn (September–October–November, (SON).

3. Results and discussion

3-1. Monthly and annual variation of lightning activity and AOD

Figure 2 shows monthly changes in the number of lightning flashes and AOD for each year from 2000 to 2014. Lightning activity in R1 and R2 reached its lowest values during summer, while AOD values in this season were maximized in most of the studied years, peaking in July (Figure 2). This may be attributed to the suppressive effect of high AOD values on convective storms and lightning (Dayeh et al., 2021). The higher AOD values observed in summer are likely related to increased frequency of dust storms during summer in southwestern Iran (Mojarrad et al., 2019).

During both transient seasons (spring and autumn), the highest number of lightning occurs in R1 and R2 (Figure 2), similar to inland regions reported by Dayeh et al. (2021). Comparatively, AOD decreased in both R1 and R2 during these seasons (Figure 2), consistent with the findings of Rezaei et al. (2019). Our analysis also indicates that AOD reaches its lowest values in winter in both studied regions (Figure 2).

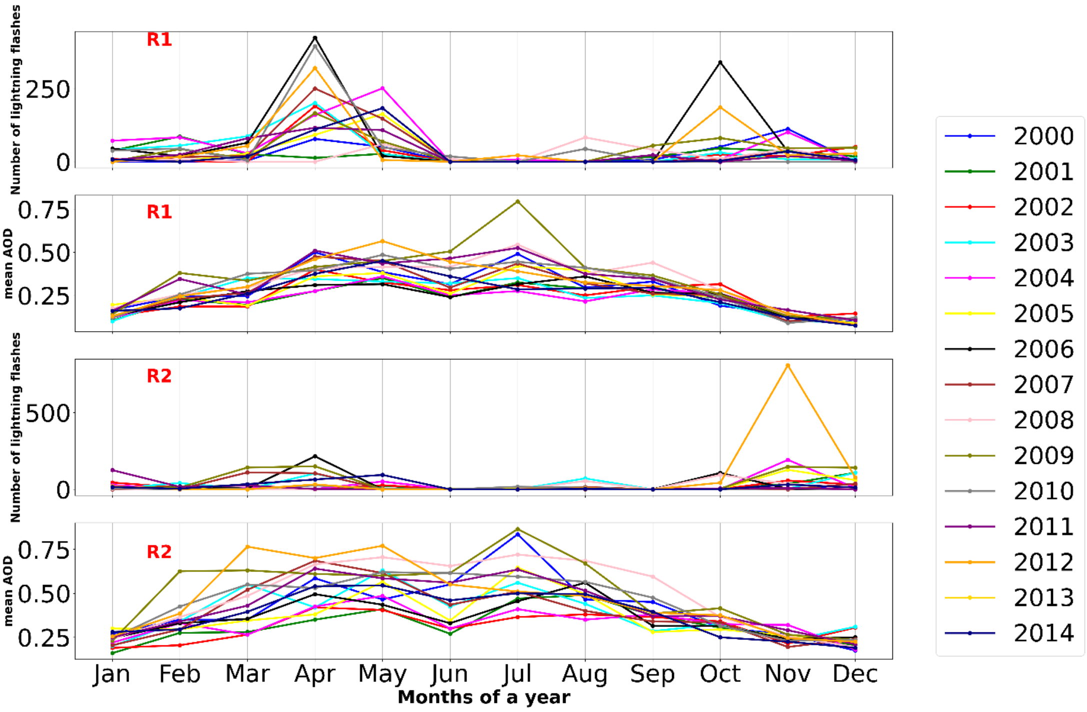
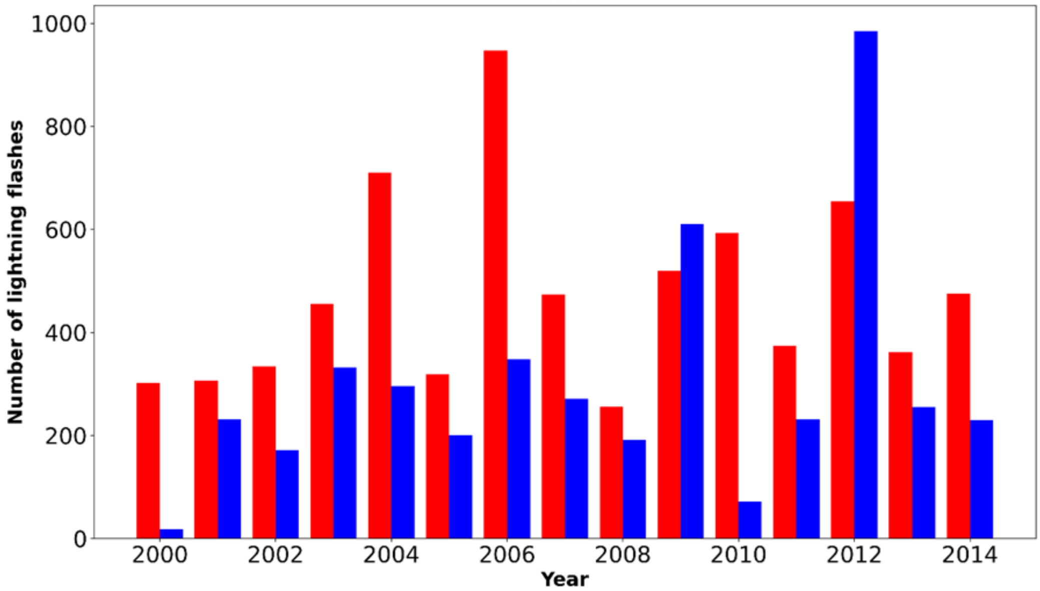
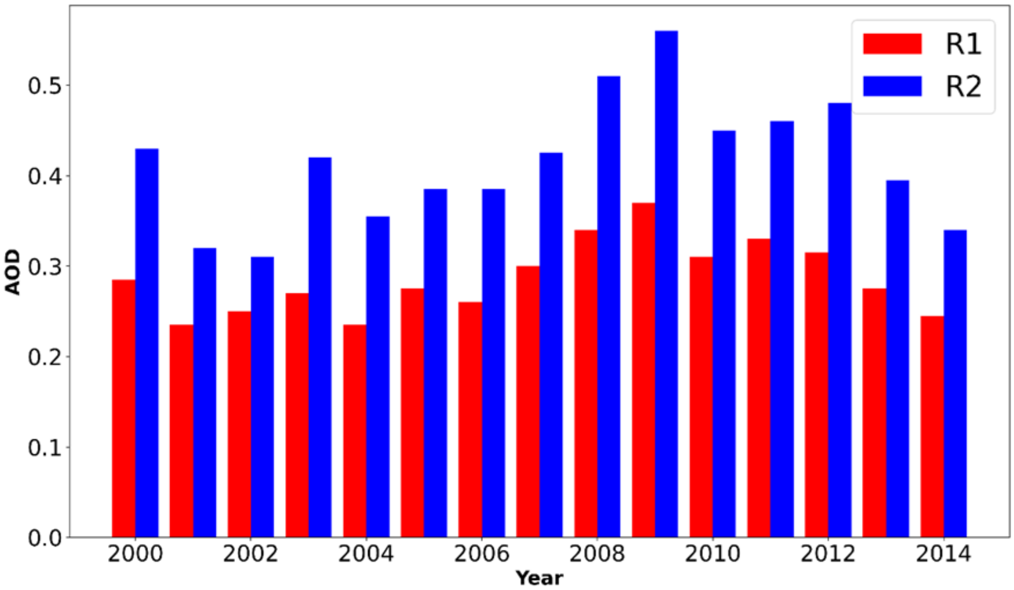


Figure 2. Monthly variations in the number of lightning events and AOD in R1 and R2 during the period 2000-2014, respectively (years are shown by different colors).

Figure 3 displays a bar graph illustrating the distribution of annual lightning events and annual average AOD in two regions, R1 and R2. The data indicate that R1 exhibits relatively twice the electrical activity of R2 (7078 compared to 4441; Figure 3a). Notably, the occurrence of sand and dust storms can be associated with the elevated lightning events in 2006 and 2012 for R1 and R2, respectively. Additionally, Figure 3b demonstrates a similar trend in both regions, with average annual AOD values initially increasing and subsequently decreasing. This suggests that both regions are primarily influenced by a common source of particles, such as dust storms. The higher AOD values observed in the coastal R2 region can be attributed to a greater number of aerosol sources compared to the primarily mountainous and desert characteristics of R1.



(a)



(b)

Figure 3. The variations in (a) the annual number of lightning occurrences and (b) the mean annual AOD in R1 and R2 regions.

3-2. Daily lightning flash variations: influences of AOD, cloud properties, and CAPE

Our analysis of lightning activity revealed significant differences between the two study regions. During the study period, from January 2000 to December 2014, R1 experienced 588 days with lightning activity, whereas R2 recorded only 353 such days. To further investigate these differences, we examined the daily average variation in the number of lightning flashes in relation to AOD, cloud fraction, ice cloud optical thickness, cloud-top height, and CAPE.

Figure 4 shows the relationship between daily averages of AOD, cloud fraction, ice cloud optical thickness, cloud-top height, and CAPE with the number of lightning flashes in R1 from 2000 to 2014. This region is mostly characterized by mountainous terrain and the arid climate of deserts. The number of flashes in this region ranges from 1 to 300 per day. To identify a trend in the data, they were rebinned, applying a selection criterion of more than 20 flashes per 24 hours.

According to Figure 4a, there is a moderate positive correlation between AOD and the number of lightning flashes, with a correlation coefficient of 0.40 at a 95% confidence level (p-value<0.05). This positive correlation indicates that the lightning flash rate increases with an increase in aerosol loading, consistent with findings reported by Mitzeva et al. (2006), Altaratz et al. (2010), Mansell et al. (2013), and Gharaylou et al. (2020). These studies showed that increasing concentrations of aerosols acting as CCN lead to a decrease in cloud droplet size inhibiting collision and coalescence processes and rain formation. Hence, a greater number of small cloud droplets can be lifted to the freezing zone by strong updrafts, where they are converted to ice particles. This increased ice particle content can then contribute to more intense lightning activity within thunderstorms by providing a larger number of potential charge separation regions and enhancing the electrical conductivity of the cloud. It is noteworthy that over 70% of R1 is characterized by mountainous terrain and is located near the Abu Ghoveyr desert in the southernmost parts of Ilam province, bordering Khuzestan province and Iraq. This region is one of the important sources of aerosol on thunderstorm days, as evidenced by studies employing dust storm identification criteria (Ranjbar et al., 2019) and desertification indicators, such as the number of days with a dust storm index (Heidarizadi et al., 2017).

There is a moderate positive correlation between the number of lightning flashes and cloud fraction (R=0.43, with 99% confidence interval) (Figure 4b), implying that the number of lightning flashes increases with an increase in cloud fraction. In other words, clouds with greater coverage tend to produce more lightning activity. The increase in aerosol loading decreases the cloud effective radius at a constant liquid water path and increases cloud albedo (Twomey, 1977; Ramanathan et al., 2001). The decrease in cloud effective radius, in turn, increases cloud lifetime and cloud fraction (Albrecht, 1989). The extended cloud lifetime enhances the chance of severe convective weather, which further increases the probability of lightning flashes (Altaratz et al., 2010; Zhao et al., 2017).

According to Figure 4c, there is a moderate positive correlation between the number of lightning flashes and ice cloud optical thickness (R=0.42, p-value<0.05), implying that strong updrafts within clouds experiencing intense lightning flashes transport greater amounts of liquid water to the upper parts of mixed-phase clouds, where more ice particles can be formed. This increase in ice particles during the electrification process contributes to an increase in lightning activity, because lightning mainly depends on charge separation resulting from collisions between larger and smaller ice particles in the upper portions of mixed-phase clouds during thunderstorms (Yair et al., 2010; Gharaylou et al., 2019).

There is a moderate positive correlation between the number of lightning flashes and cloud height (R=0.39, with 95% confidence interval) (Figure 4d). In other words, clouds characterized by strong convection and greater cloud-top heights tend to produce more lightning, a finding consistent with the observations of Altaratz et al. (2010) and Zhao et al. (2017).

To investigate the relationship between CAPE and lightning activity, CAPE values from days with lightning at 12:00 UTC during the period

2000-2014 were analyzed. Figure 4e illustrates the lightning activity for different CAPE values along with a linear regression line. This figure indicates a positive correlation between the number of lightning flashes and CAPE, with a correlation coefficient of 0.39, suggesting a link between lightning activity and thermodynamic instability. These results emphasize the significance of CAPE as a predictor of lightning activity, highlighting the critical role of thermodynamic conditions in storm development and lightning occurrence (Williams and Stanfill, 2002).

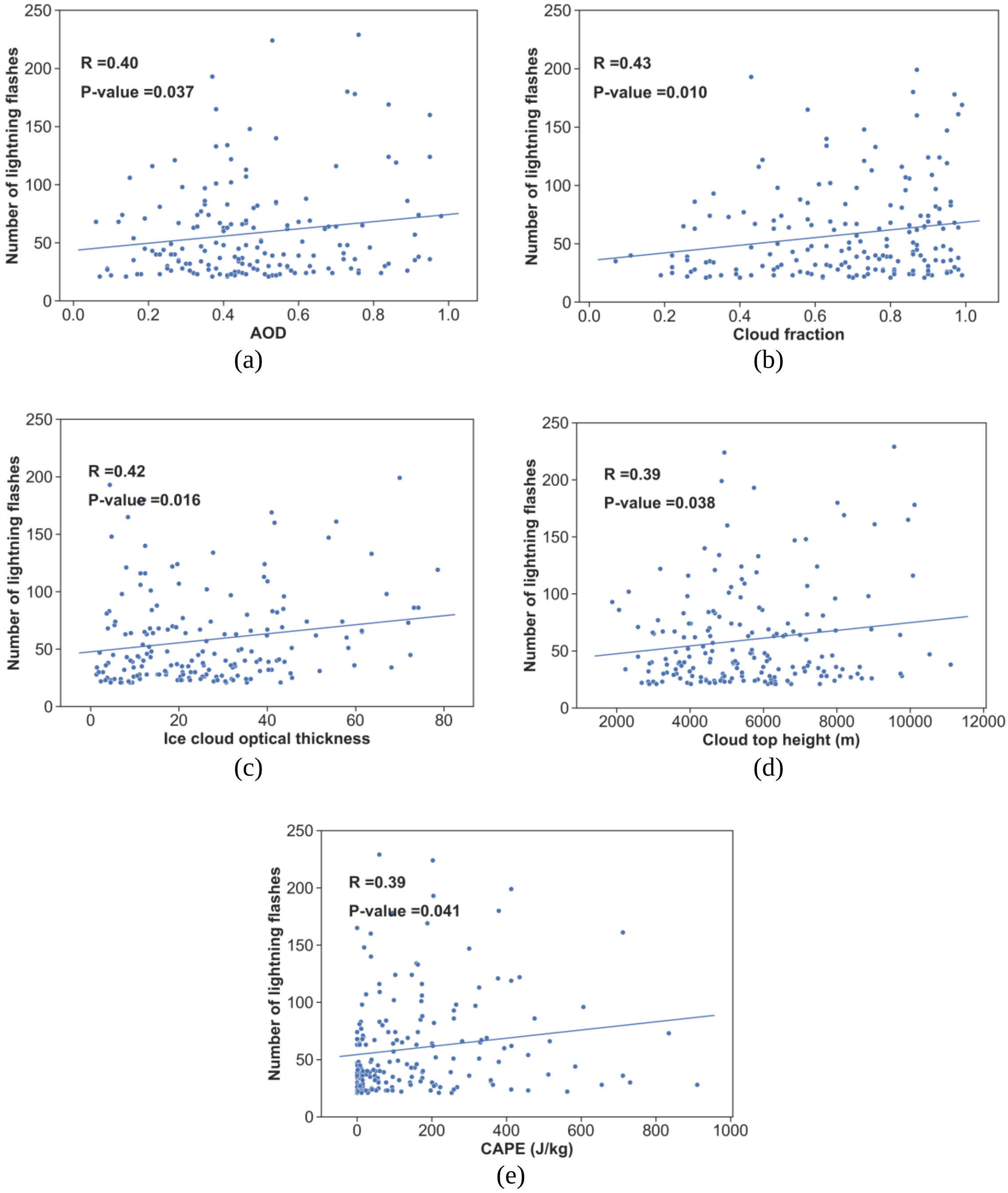
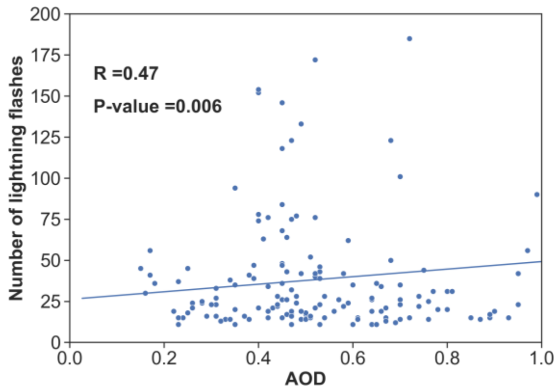


Figure 4. The scatter diagram of the number of lightning flashes and the daily average of (a) AOD, (b) cloud fraction, (c) ice cloud optical thickness, (d) cloud-top height (m), and (e) CAPE (J/kg) during the period 2000-2014 in R1. Values of correlation coefficients (R) and significance level (p-value) are also given in each panel.

Figure 5 shows the correlation between the daily average of AOD, cloud fraction, ice cloud optical thickness, cloud-top height, and CAPE with the number of lightning flashes in the coastal region of R2 during the period 2000-2014 in R2. Similar to Figure 4, to achieve a trend in data, a limitation was applied on lightning data. Given the lower frequency of lightning events in R2 (353 days with lightning) compared to R1 (588 days), a threshold of 10 lightning flashes per day was used for R2. There is a positive correlation between AOD and the number of lightning flashes (R=0.47, with 99% confidence interval), (Figure 5a), implying that the number of lightning flashes increases with an increase in aerosol loading, which is similar to Figure 4a for R1.

Similar to Figure 4b, there is a positive correlation between the number of lightning flashes and cloud fraction in R2 (Figure 5b). There is also a positive correlation (R=0.42, p-value<0.05) between the number of lightning flashes and ice cloud optical thickness in the coastal region of R2 (Figure 5c), which is consistent with findings of Zhao et al. (2017). They showed that an increase in ice particles during the electrification process leads to an increase in electrical activity.

In the coastal area of R2, weak positive correlations exist between the number of lightning strikes and both cloud-top height (R=0.14) and CAPE (R=0.11) (Figure 5d and 5e, respectively). This is expected because clouds that are more vertically developed have more droplets that grow bigger and bump into each other more often, thereby transferring more charge and mixing less (Williams et al., 1989). Also, supercooling occurs below the freezing point at higher altitudes within clouds increases the likelihood of lightning. Coastal areas typically have higher humidity and moisture levels, which can create more stable atmospheric conditions. This stability tends to decrease the occurrence and severity of thunderstorms. Consequently, there is less transport of supercooled water to the freezing level and fewer ice particles form, leading to an increase in total liquid water content. This, in turn, weakens the correlation between CAPE and lightning (Zhao et al., 2020; Yadava et al., 2023; Qie et al., 2024).



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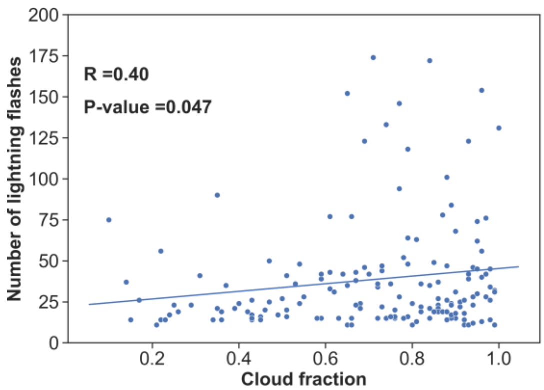

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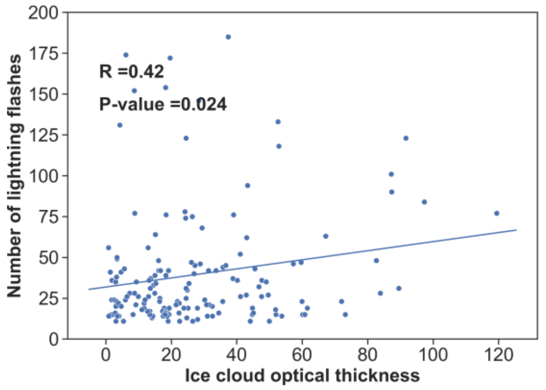

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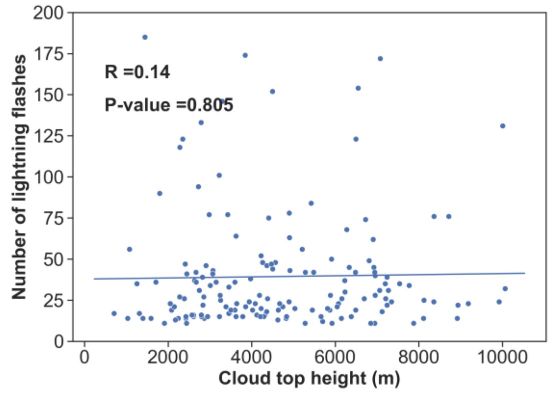

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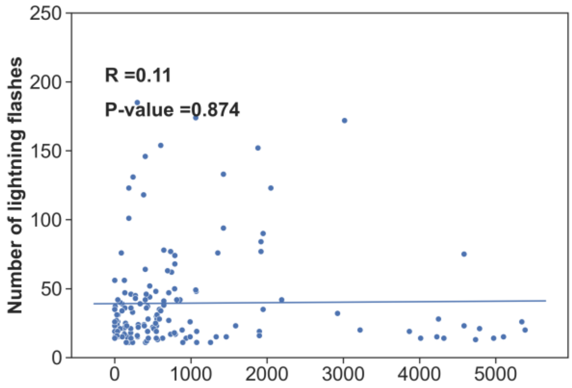


(e)

Figure 5. The scatter diagram of the number of lightning flashes and the daily average of (a) AOD, (b) cloud fraction, (c) ice cloud optical thickness, (d) cloud-top height (m), and (e) CAPE (J/kg) during the period 2000-2014 in R2. Values of correlation coefficients (R) and significance level (p-value) are also given in each panel.

In addition to examining the mean daily variation of the number of lightning flashes against AOD, cloud fraction, ice cloud optical thickness, cloud-top height, and CAPE, it is essential to explore how these relationships vary across different seasons. Table 1 presents the correlation coefficients between these parameters and the number of lightning flashes for each of the four seasons—spring, summer, autumn, and winter.

When examining the correlations between R1 and R2, it is observed that AOD in R1 has significant positive correlations in spring (0.19) and autumn (0.13), while in R2, the highest positive correlation for AOD is noted in spring (0.31). Both regions exhibit negative correlations during summer, with R1 at -0.17 and R2 at -0.16. Regarding cloud fraction, R1 shows significant positive correlations in autumn (0.21) and spring (0.15), whereas R2 follows a similar pattern with positive correlations in spring (0.18) and autumn (0.15), although it exhibits a slightly negative correlation in summer (-0.09). Ice cloud optical thickness in R1 maintains positive correlations across all seasons, peaking in summer (0.19), while R2 mostly mirrors this trend but shows a slight negative correlation in summer (-0.03). Regarding the cloud-top height, R1 shows strong positive correlations, particularly in summer (0.23), while R2 shows mixed results, with a peak in summer (0.12). For CAPE, R1 demonstrates strong positive correlations in summer (0.28) and spring (0.26), while R2 exhibits a significantly higher positive correlation in winter (0.33) and weaker positive values in summer (0.17) and autumn (0.19). These comparisons underscore the variability and seasonal dynamics in correlations between the two regions, highlighting their unique environmental influences.

Table 1. Correlation coefficients between the number of lightning flashes and AOD, cloud fraction, ice cloud optical thickness, cloud-top height, and CAPE for spring, summer, autumn, and winter.

Parameter	Spring (R1)	Summer (R1)	Autumn (R1)	Winter (R1)	Spring (R2)	Summer (R2)	Autumn (R2)	Winter (R2)
AOD	0.19	-0.17	0.13	0.02	0.31	-0.16	0.01	-0.02
Cloud fraction	0.15	-0.04	0.21	0.05	0.18	-0.09	0.15	0.08
Ice cloud optical thickness	0.16	0.19	0.17	0.06	0.24	-0.03	0.22	0.08
Cloud-top height	0.06	0.23	0.17	0.01	-0.00	0.12	0.08	-0.02
CAPE	0.26	0.28	0.17	0.19	0.05	0.17	0.19	0.33

Figures 4b-c and 5b-c show similar trend for cloud fraction and ice cloud optical thickness in both R1 and R2, indicating that aerosols do not significantly affect these variables. However, AOD and cloud-top height are not the same (Figures 4a, d and 5a, d), likely due to different weather and landscape in the two regions. R1 proximity to Iraq and Abu Ghoveyr desert suggests a higher prevalence of dust, wildfires, and anthropogenic aerosols compared to R2. R2 coastal location implies that its primary aerosol sources are mostly sea salt, anthropogenic aerosols from ships, and dust from deserts in Kuwait and the Arabian Peninsula. To show the aerosol sources in each region, latitude/longitude distributions of AOD for BC, mineral dust, sea salt, and sulphate were plotted using MACC-II data (Figure 6). In this regards, the contribution of AOD with BC source averaged over R1 and R2 has been calculated. The values of 0.01 for R1 and 0.01 for R2 show that the effect of AOD with BC source are similar (Figure 6a). Figure 6b shows that R2 experiences a greater amount of dust compared to R1 region, with dust AOD values of 0.12 for R1 compared with 0.15 for R2. Although R2 is a coastal region, Figure 6c shows that R1 was affected by a higher amount of AOD with sea salt source during the studied period (0.005 for R1 compared with 0.004 for R2). However, the coastal nature of R2 resulted in a higher influence of sulphate AOD (0.11) compared to R1 (0.09) (Figure 6d).

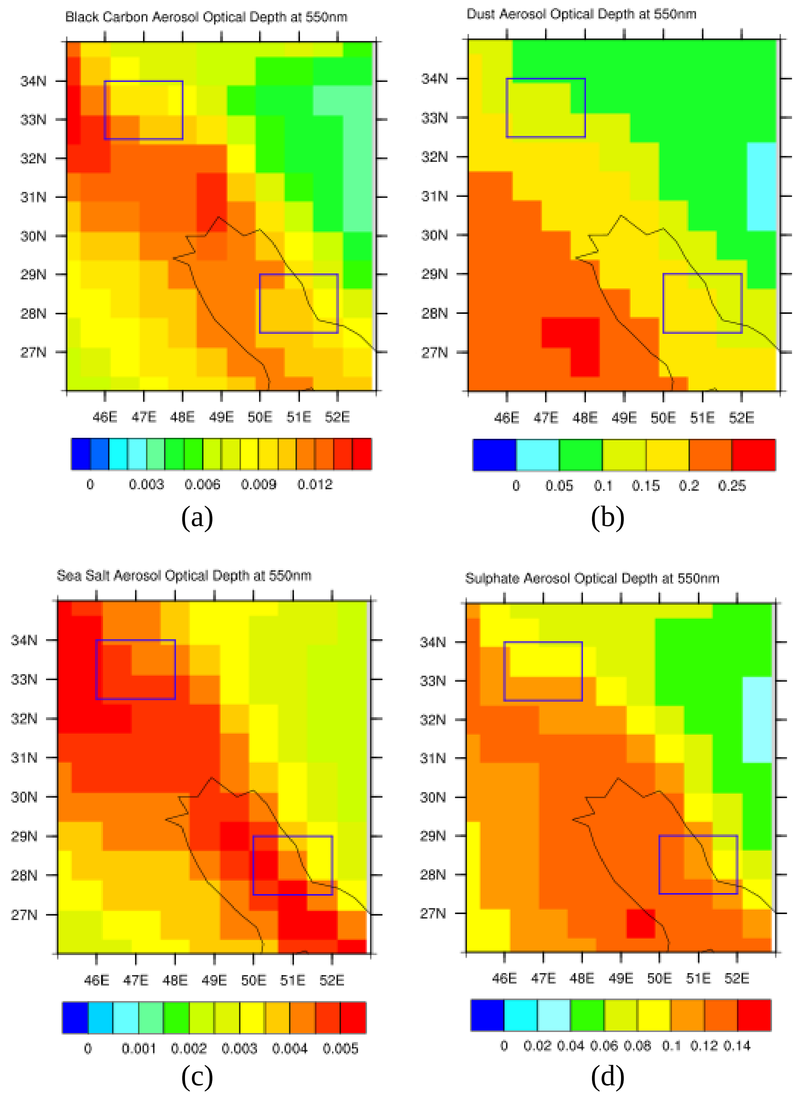
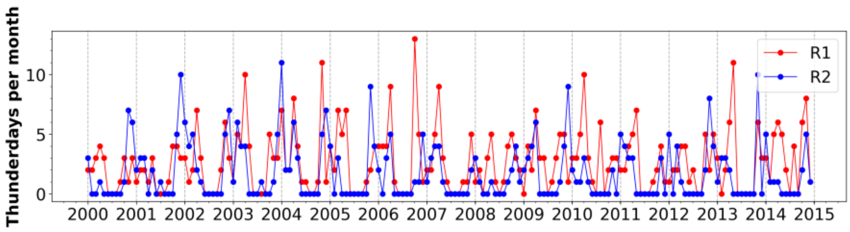
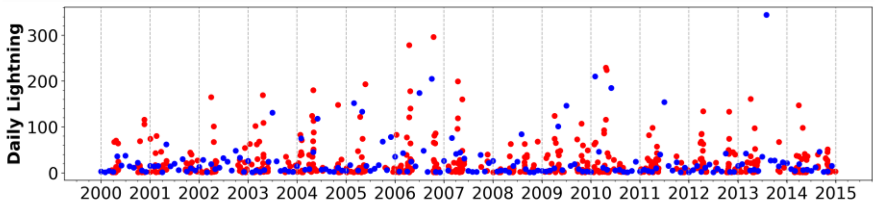


Figure 6. The horizontal patterns of averaged AOD for (a) BC, (b) mineral dust, (c) sea salt, and (d) sulphate from MACC reanalysis data during 2003 to 2012.

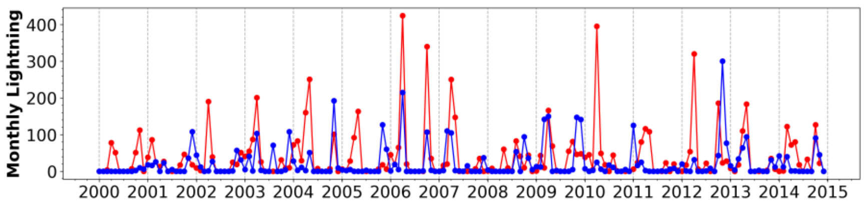
Figure 7 shows the number of lightning flashes and AOD on a daily and monthly basis, as well as the number of thunder days per month for the period 2000-2014. While R1 and R2 experienced different levels of electrical activity, the timing of these events coincided in both regions (Figure 7a-b). There was more lightning in spring (April and May), autumn, and winter (October and November) in both regions (Figure 7b). The highest numbers of lightning flashes occurred in 2006 in R1 and 2012 in R2. Rafati and Fattahi (2022) also found that lightning density is relatively higher in May and December in southwestern Iran for the period 1996-2014. Figures 7c-d show the daily and monthly variations in AOD. There was larger values of AOD in R2 than R1, such that monthly AOD varied from 0.1 to 0.6 in R1 and from 0.1 to 0.8 in R2 (Figure 7d). Dust likely influences AOD values in R1 due to the region's dry to semi-dry climate and proximity to dust sources in Iraq (Namdari et al., 2016). Nevertheless, different factors contributed to AOD values in R2, e.g. presence of big ports along the coastlines of the Persian Gulf with ship-source pollutants, anthropogenic pollution of Bushehr port, industrial pollutants, power plants, and refine of huge gas. Figure 7b, d suggests that higher aerosol concentrations can influence cloud development and the number of ice crystals, thereby contributing to increased lightning activity. Nevertheless, a huge number of aerosols may reduce lightning by blocking or changing sunlight. Wang et al. (2021) and Dayeh et al. (2021) found similar results. We also calculated thunder days defined as days with at least one lightning flash within a 24-hour period in each region (Figure 7h). Our analysis indicates a higher frequency of thunder days in both regions during April, May, October, and November consistent with the findings of Araghi et al. (2016) and Mojarrad et al. (2019), who reported that thunderstorms primarily occurred during the colder months of the year (November to March), and less frequently during the warmer months (April to October).



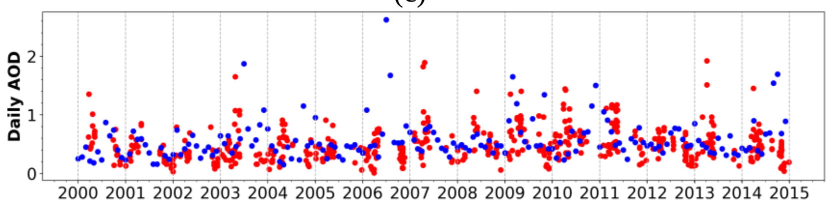
(a)



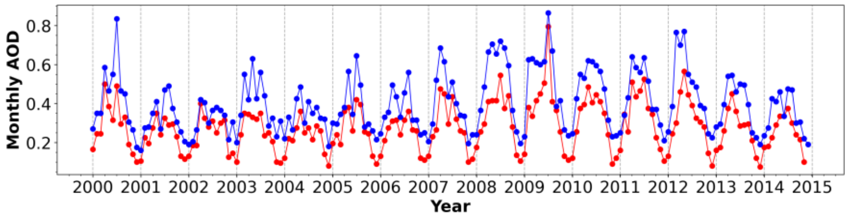
(b)



(c)



(d)



(e)

Figure 7. Temporal variations of (a) the number of thunder days per month, (b) daily lightning flashes, (c) monthly lightning flashes, (d) daily AOD, and (e) monthly AOD during the period 2000-2014.

4. Conclusions

This study investigated the influence of aerosols, thermodynamics and cloud characteristics on lightning activity during thunderstorm events in western Iran from 2000 to 2014. Using MODIS data, ERA5 data, and the LIS imaging sensor, we retrieved cloud fraction, ice cloud optical thickness, cloud-top pressure and temperature, AOD, CAPE, and lightning flash density during thunderstorm days in two distinct regions: R1 and R2. Over this period, we identified 588 lightning days in R1 and 353 lightning days in R2.

This study highlights the intricate interaction between aerosols, thermodynamic parameters, and cloud characteristics in influencing lightning activity in western Iran. The seasonal patterns observed, with peak lightning activity in spring and autumn and a notable decrease during summer, highlight the influence of dust storms on AOD and subsequent thunderstorm dynamics.

The moderate positive correlation between AOD and cloud fraction suggests that increased aerosol loading can enhance lightning activity, particularly in regions with extensive cloud coverage. This suggests that atmospheric aerosols not only influence cloud formation but also play a significant role in enhancing storm dynamics. As ice particles form more readily in the presence of aerosols, the resulting increase in electrical activity could lead to more frequent and intense lightning strikes (Altaratz et al., 2010; Zhao et al., 2017 and 2020). The observed positive correlation between lightning flash density and ice cloud optical thickness further supports the concept that strong updrafts in severe thunderstorms are crucial for transporting moisture to higher altitudes, where ice formation occurs. Conversely, the weaker correlation between cloud-top height and lightning density in R2 emphasizes the impact of a cleaner atmosphere, which may limit the strength of updrafts and consequently reduce electrical activity (Altaratz et al., 2010). Our CAPE analysis supports the understanding that higher CAPE values correlate with increased lightning flashes, although this relationship is moderated in coastal areas due to the stabilizing effects of higher humidity (Zhao et al., 2020; Yadava et al., 2023).

In summary, the findings suggest that variations in terrain and aerosol sources across regions significantly influence lightning activity, with R1 experiencing almost twice as many annual lightning events as R2. This conclusion is supported by Zhao et al. (2020), who emphasized that aerosol loading affects lightning in plateau and basin regions differently, altering convective activity and lightning density.

This research contributes to a broader understanding of how atmospheric conditions, particularly in arid and semi-arid regions, influence thunderstorm behavior and lightning frequency. Future studies could further explore the implications of these findings for climate modeling and weather prediction, particularly in light of changing aerosol concentrations due to both human activity and natural phenomena.

Data Availability Statement

We obtained the observed lightning data from https://lightning.nsstc.nasa.gov/nlisib/nlisbrowsecal.pl?which=qc) and the cloud fraction, ice cloud optical thickness, cloud-top pressure and temperature, AOD data from http://modis-atmos.gsfc.nasa.gov, and CAPE data from the European Centre for Medium-Range Weather Forecasts (ECMWF; https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-single-levels?tab=form/).

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