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 LIS, cloud fraction, cloud-top height, ice cloud optical thickness, and AOD data from MODIS, and CAPE from the ERA5 data for the period 2000-2014 in two distinct environmental areas (R1 and R2). R1 is located between 32.5°N and 34°N and 46°E and 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 and 29°N and 50°E and 52°E, is characterized by plains with a warm and dry climate in the north and a humid, warm climate in the south. Analysis of monthly variations indicates 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 values. Analysis of annual variation of lightning activity and AOD indicates that electrical activity is higher in R1, which frequently experiences sand and dust storms. The results showed that AOD has a moderate positive correlation with lightning activity in both regions due to various AOD sources, including black carbon, dust, sea salt, and sulphate. Cloud fraction, ice cloud optical thickness, and cloud-top height have a positive correlation with lightning density in R1 and R2, while the correlation between CAPE and lightning density is lower in R2, likely due to higher humidity stabilizing the atmosphere leading to fewer and less intense thunderstorms.

Keywords: Aerosols, lightning, AOD, cloud properties, CAPE

1. Introduction

During thunderstorms, many solid aerosol particles may lift from the ground and significantly contribute to changes in the microphysical processes of clouds. These particles are released into the thundercloud and can serve as cloud condensation nuclei (CCN). An increase in the concentration of aerosols can also delay convection and the onset of precipitation and reduce the size of cloud ice particles (Khain et al., 2005).

Changes in cloud microphysics may lead to a delay in cloud glaciation, which leads to colder temperatures and results in an increase in lightning flashes (Yoshida et al., 2009; Yuan et al., 2011).

Several studies have been conducted to investigate the relationship between aerosols and lightning. some of them reported 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 influence lightning activity, potentially modifying the frequency, intensity, and distribution of lightning strikes by changing the electrical properties of clouds and the atmospheric electrical environment.

The study of 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 increases in large cities and their downstream due to anthropogenic aerosol emissions. Lyons et al. (1998) investigated the impact of wildfire smoke on cloud-to-ground lightning from April to June 1998. The smoke originated from southern Mexico and was transported northward into the southern plains of the United States. Their results revealed that smoke largely influences the intensity of lightning and increases the percentage and maximum current of positively charged cloud-to-ground lightning. In a subsequent study, Fernandes et al. (2006) and Altaratz et al. (2010) conducted similar studies and discovered that an increase in the concentration of smoke results in an increase in electrical activity. Lal and Pawar (2011) used satellite data from the Moderate Resolution Imaging Spectroradiometer (MODIS) and the Tropical Rainfall Measuring Mission (TRMM) to study the relationship between lightning activity and aerosol optical depth (AOD) in four major cities in India. Their results showed that lightning intensity increases by the combined impact of cloud thermodynamics and aerosols in urban areas, while the impact of aerosols on lightning is not noticeable in coastal cities. Wang et al. (2011) found 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 link 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. Meanwhile, the microphysical effect of aerosols may play a significant role in increasing 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), there is a significant relationship between lightning and AOD which 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) noted that a decrease in surface pollution concentrations has a significant impact on lightning activity in Kolkata. Gautam et al. (2021) investigated the relationship between aerosol and lightning in the southern parts of India for the period from 2017 to 2020. They concluded 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 and discovered a positive linear relationship between AOD and lightning activity. They found that under low AOD values, the relationship between AOD and lightning is linear, and the air-cloud interactions are the primary factor influencing lightning activity under relatively clean conditions. Under higher AOD values, both aerosol-cloud and aerosol-radiation interactions, which depend on AOD properties such as the type and size of aerosols, may inhibit convection and lightning activity. The results of Dayeh et al. (2021) also revealed that the linear relationship between AOD and lightning is much stronger in mountainous regions than in 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), which can enhance or suppress the conditions needed for lightning formation by affecting the distribution and intensity of electric charges within the clouds.

Due to the complexity of the effects of aerosols on lightning activity and cloud microphysics, the possible effects of aerosols on thunderstorms need to be further studied. We investigate the effect of aerosols, cloud properties, and CAPE on lightning activity in the western part of Iran, where the number of lightning flashes is relatively high, with an average lightning strike of 6-10 per square kilometer per year during 1998-2015 (Cecil et al., 2014). We also examine the relationship between lightning flash density, some 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 $1^{\circ}\times 1^{\circ}$ for the period 2000 to 2014 are used. The accuracy of the 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/) have been used. The LIS on the Tropical Rainfall Measuring Mission (TRMM) satellite detect optical emissions from lightning. It operated for 17 years until 2015, providing global lightning data within ±38° latitude. The LIS/OTD combined product has been previously validated and documented in Cecil et al. (2014). The detection efficiency of LIS is 73% and 93% during daytime and nighttime, respectively (Cecil et al., 2014). CAPE, serves as a crucial indicator of atmospheric stability and convective storms. It 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, we also obtained CAPE data from the ERA5 reanalysis for the period 2000 to 2014. ERA5, the fifth generation of global atmospheric reanalysis produced by ECMWF (Hersbach et al., 2020), offers 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 kinds of aerosols (black carbon (BC), mineral dust, sea salt, and sulphate) have been extracted from the MACC-II (Monitoring Atmospheric Composition and Climate Interim Implementation) reanalysis data produced by the ECMWF (European Centre for Medium-Range Weather Forecasts) in the period of 2003 to 2012. The horizontal resolution of MACC-II data is 1 degree in both longitude and latitude directions in 6 hours interval.

2.2 Study area

Figure 1 shows the topographic map of the study area. We divided the research area into two regions with distinct geographical and climatic conditions, hereafter referred to as R1 and R2. R1 is located between

32.5°N and 34°N and 46°E and 48°E (in the west of Iran). This area is a mountainous region, but its climate is also influenced by the deserts in its west and south. R1 experiences three different types of climates, including Mediterranean (moderate), cold mountainous, and warm semi-desert climates. R2 is located between 27.5°N and 29°N and 50°E and 52°E. This region is plain with various climate, warm and dry climate in north and humid and warm in south, with intense evaporation due to the long summer season (Pegahfar, 2022). The reason for the selection of these two regions is the occurrence of relatively large number of thunderstorms and lightning (Ghalhari and Shakeri, 2015). In addition, in these regions, we can investigate the impact of aerosols on lightning in two regions with diverse climates.

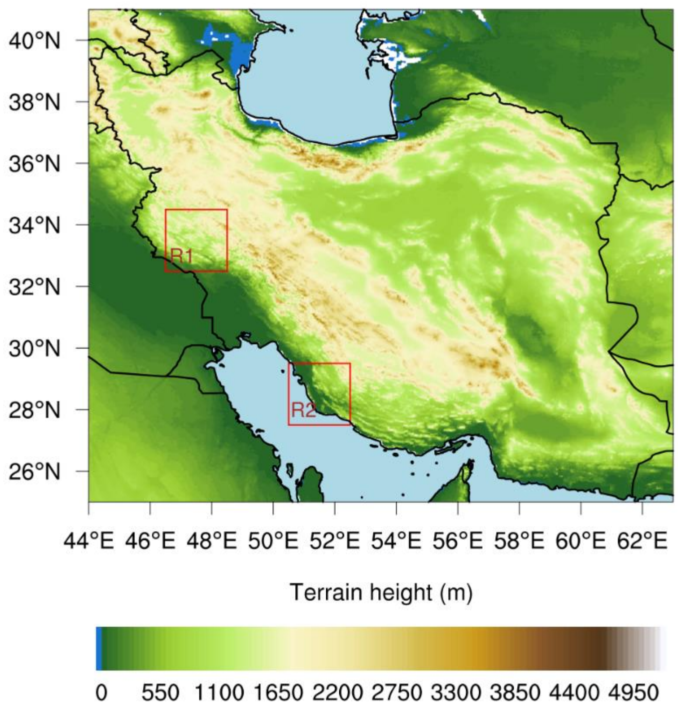


Figure 1. The topographic map (meters) of the study area. Red rectangles show the geographic locations of the studied regions.

2.3 Methods

We first identified the days of lightning activity during the period from January 2000 to December 2014, which are defined as days with at least one lightning strike within a 24-hour period. The LIS orbit passing from the both studied regions were tracked in 1 degree grids, computing the number of flashes at each pixel during the orbit passage. Then, we extracted the average values of AOD during these days of lightning activity 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 considered parameters, varying from -1 (representing a negative correlation) to 1 (representing a positive correlation), where 0 signifies no correlation. Mindrila and Balentyne (2017) indicate that a correlation coefficient below 0.3 signifies a weak positive relationship, between 0.3 and 0.7 indicates a moderate positive relationship, and above 0.7 denotes a strong positive relationship between two variables, even if their scatterplot appears dispersed. Furthermore, a p-value less than 0.01 or 0.05 signifies that the correlation is statistically significant 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 in each year from 2000 to 2014. The Lightning activity in R1 and R2 reached the lowest values in summer, while AOD values in this season is maximized in most of studied years with the peak in July (Figure 2). It may be due to the suppression effect of convective storms and lightning under high AOD values (Dayeh et al., 2021). The higher values of AOD in summer are related to the more frequent dust storms in summer in southwestern Iran (Mojarrad et al., 2019).

In both transient seasons (spring and autumn), the largest number of lightning occurs in R1 and R2 (Figure 2), similar to inland region of Dayeh et al. (2021). Comparatively, AOD decreased in these seasons both in R1 and R2 (Figure 2) consistent with the results of Rezaei et al. (2019). Our analysis also indicates that AOD have a smallest values in winter in both studied regions (Figure 2).

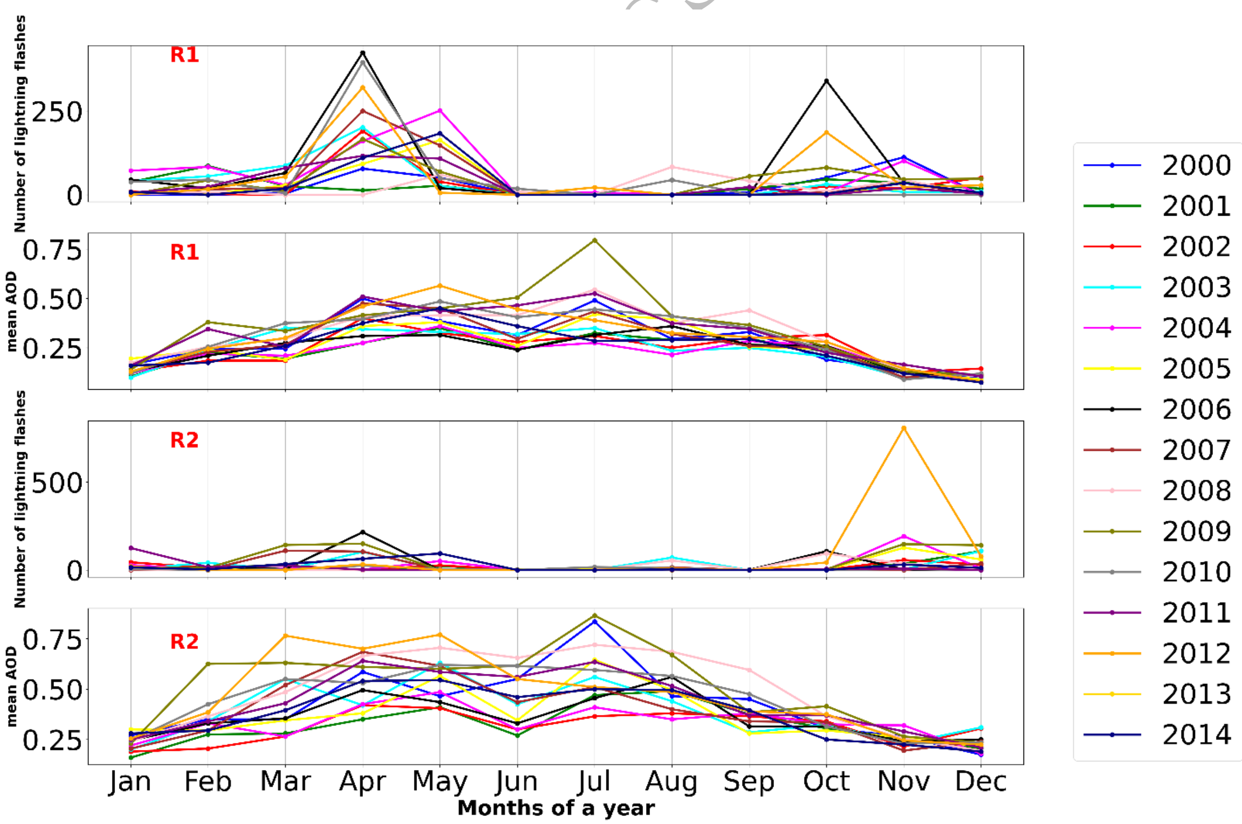
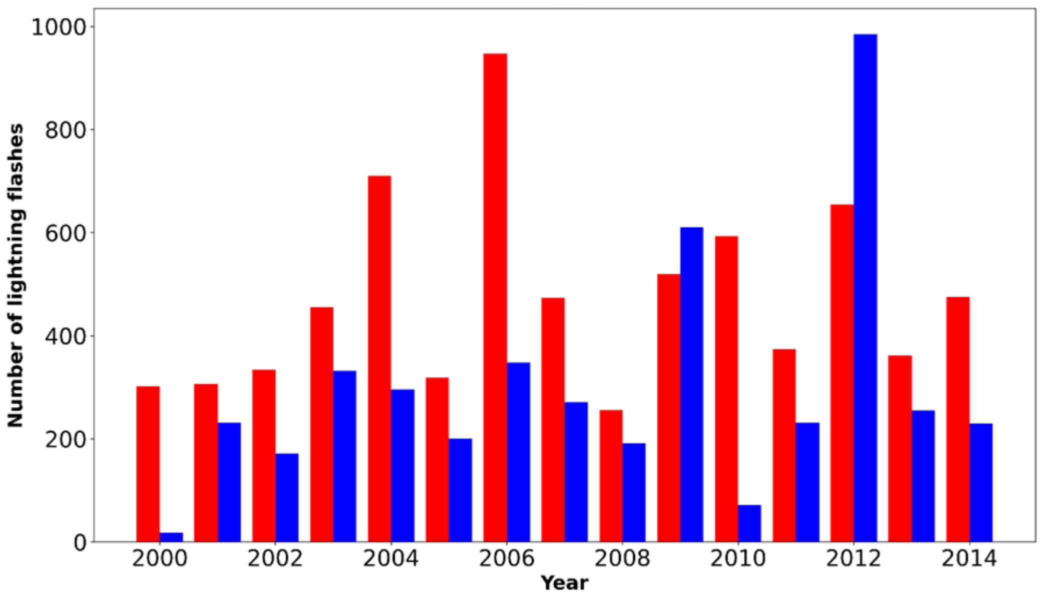


Figure 2. Monthly variation in the number of lightning events and AOD in R1 and R2 during the period 2000-2014, respectively (year are shown in different colors).

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 indicates that the R1 region exhibits relatively twice electric activity compared to 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 the average annual AOD values initially increasing, followed by a subsequent decrease. 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 larger number of aerosol sources, in contrast to the primarily mountainous and desert characteristics of the R1 region.



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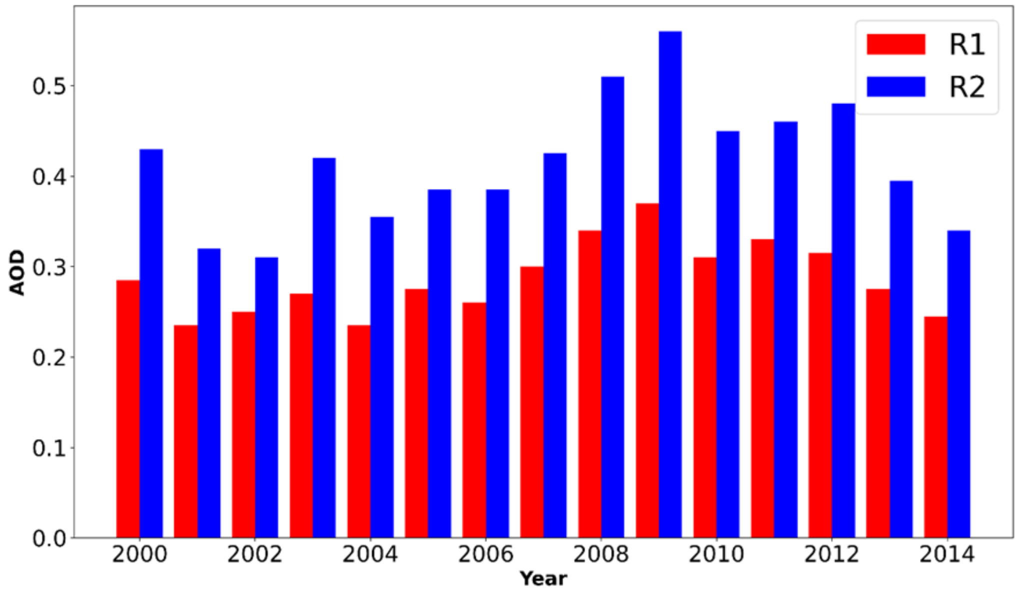


(b)

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 of lightning activity, whereas R2 recorded only 353 days of lightning activity. To further investigate these differences, we examined the daily average variation of the number of lightning flashes in relation to AOD, cloud fraction, ice cloud optical thickness, cloud-top height, and CAPE.

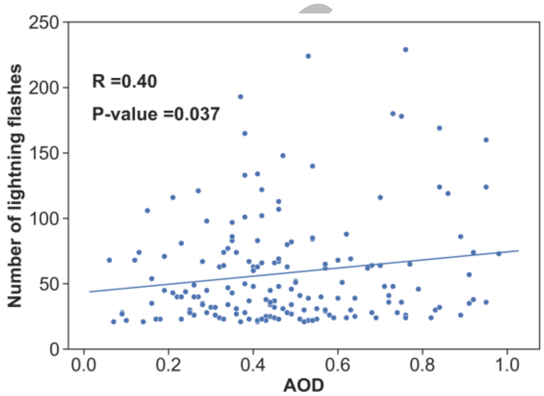
Figure 4 shows the relationship between the daily average of AOD, cloud fraction, ice cloud optical thickness, cloud-top height, and CAPE with the number of lightning flashes in R1 from 2000 to 2014. This region is mostly characterized by mountainous terrain and the dry climate of deserts. The number of flashes for this region ranges from 1 to 300 per day. To identify a trend in the data, they have been rebinned and a selection criterion of more than 20 flashes per 24 hours has been applied.
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 95% level of confidence ($p\text{-value}<0.05$). This positive correlation indicates that the lightning flash rate increases with an increase in aerosol loading, which is consistent with the results of Mitzeva et al. (2006), Altaratz et al. (2010), Mansell et al. (2013), and Gharaylou et al. (2020). They showed that with an increase in the concentration of aerosols that act as CCN, the cloud droplet size decreases. This prevents collision and coalescence processes and rain formation. Hence, a large number of small cloud droplets can be lifted to the freezing zone by strong updrafts where they are converted to ice particles. The increased ice particle content can then contribute to more intense lightning activity in thunderstorms, as it provides a larger number of potential charge separation regions and enhances the electrical conductivity of the cloud. Noteworthy that more than 70% of R1 is characterized

by mountainous terrain and located near the Abu Ghoveyr desert in the southernmost parts of Ilam province and the border of Khuzestan province and Iraq. This region is one of the important sources of aerosols on thunder days by investigating some dust storm identification criteria (Ranjbar et al., (2019) and also based on the desertification indicators such as the number of days with 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 more extensive coverage produce more lightning activity. The increase in aerosol loading decreases the cloud effective radius at constant liquid water path and increases the cloud albedo (Twomey, 1977; Ramanathan et al., 2001). The decrease in cloud effective radius increases the cloud lifetime and the cloud fraction (Albrecht, 1989). Increase in the lifetime of cloud enhances the chance of severity of convective weather that further increases the possibility 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 in clouds with intense lightning flashes carry more liquid water to the upper parts of mixed-phase clouds where more ice particles can be formed. An increase in ice particles in the electrification process contributes to an increase in lightning activity because lightning mainly depends on charge separation resulting from collisions between large and small ice particles in the upper parts 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 that are characterized by strong convection and high cloud-top heights produce more lightning, as also noted by 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 that the number of lightning flashes increases with rising 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 for lightning activity, highlighting the critical role of thermodynamic conditions in the development of storms and the occurrence of lightning (Williams and Stanfill, 2002).



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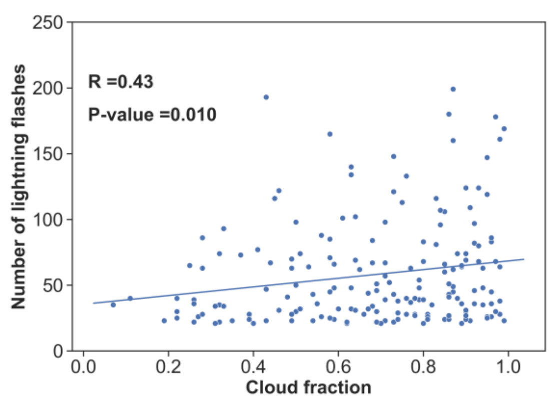

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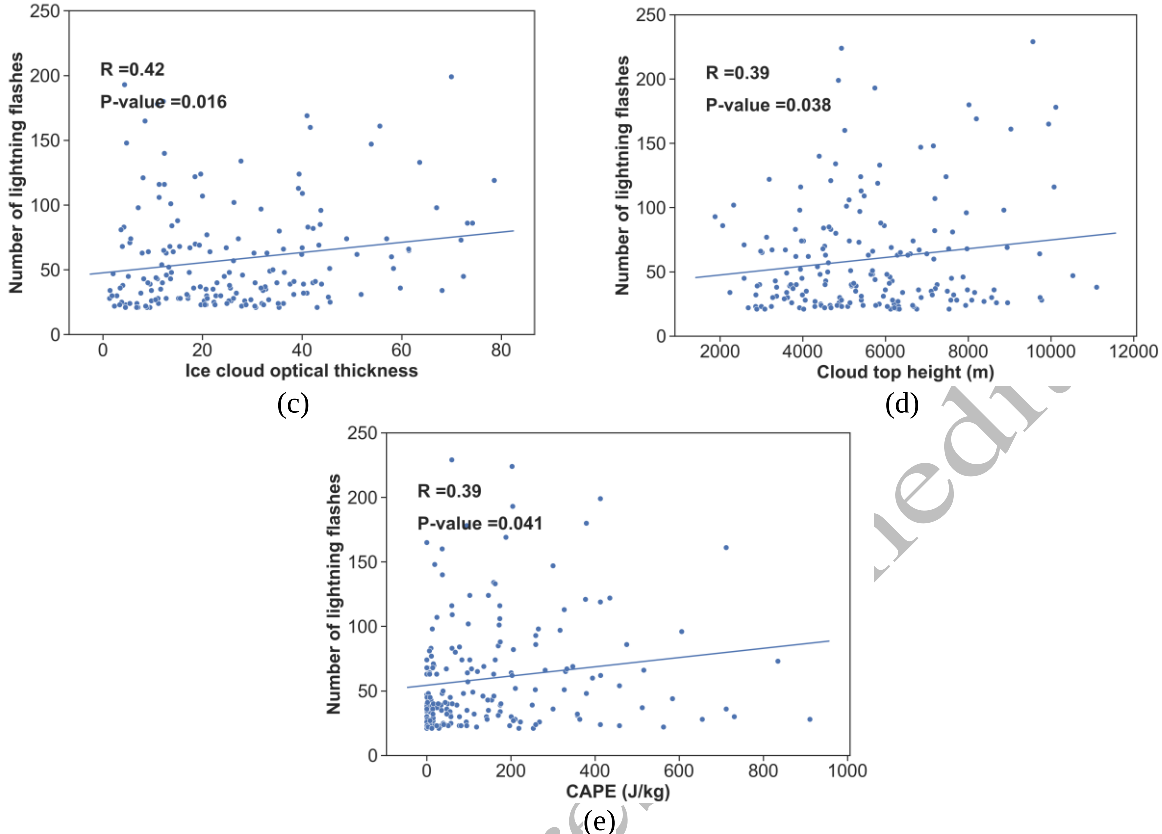


Figure 4. The scatter diagram of the number of lightning flashes and the daily average of (a) AOD, (b) cloud fraction, (c) ice cloud optical thickness, (d) cloud-top height (m), and (e) CAPE (J/kg) during the period 2000-2014 in R1. Values of correlation coefficients (R) and significance level (p-value) 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 that the R2 region experienced less days with lightning occurrences during the study period (353 days for R2 compared to 588 days for R1), the limit of 10 lightning flashes per day for R2 was considered. 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 the results of Zhao et al. (2017). They showed that an increase in ice particles in the electrification process leads to an increase in electrical activity.

In the coastal area of R2, there is a slight positive correlation between the number of lightning strikes and the 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 in higher parts of clouds, which makes lightning more likely. Coastal areas typically have higher levels of humidity and moisture, 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).

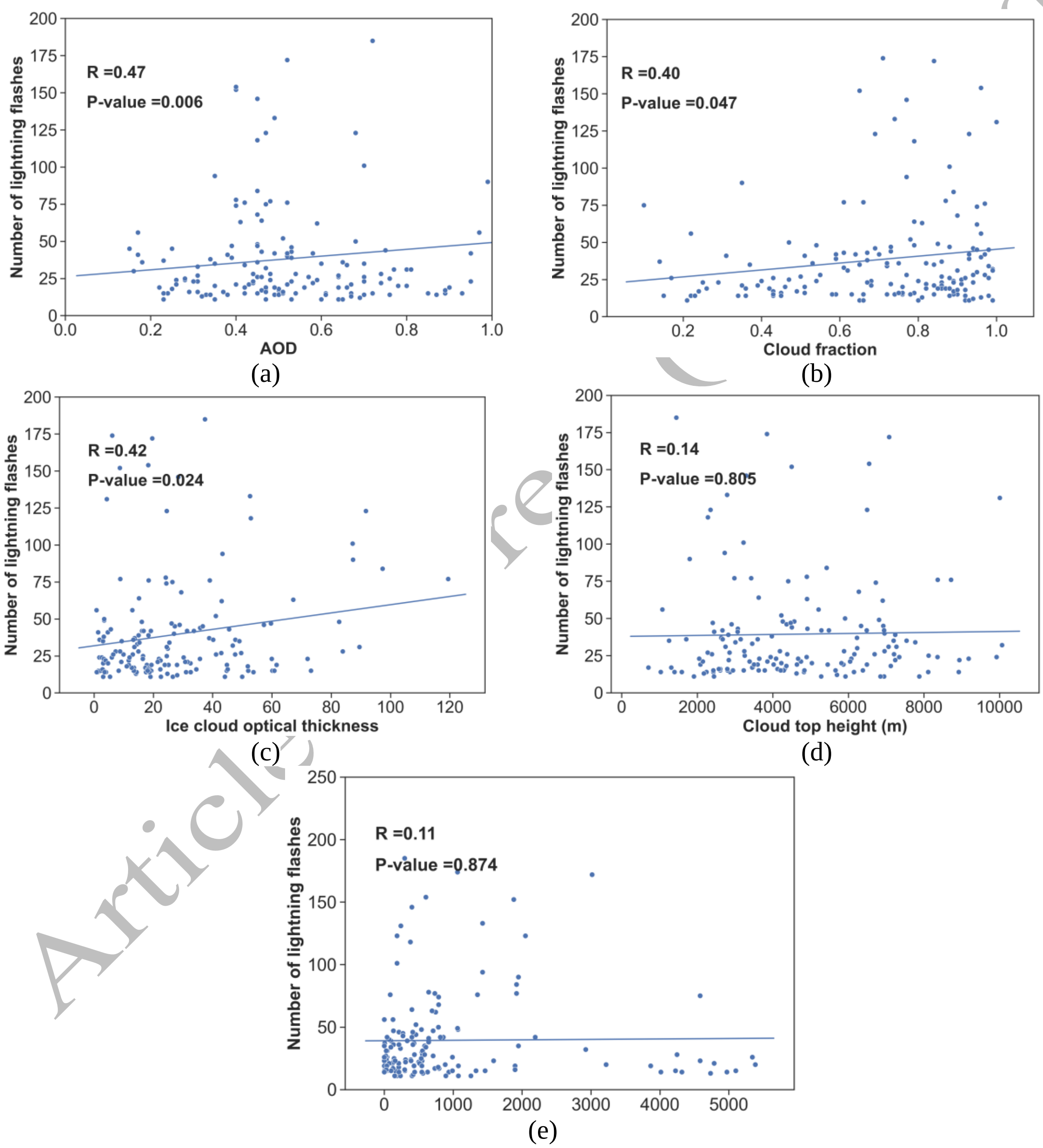


Figure 5. The scatter diagram of the number of lightning flashes and the daily average of (a) AOD, (b) cloud fraction, (c) ice cloud optical thickness, (d) cloud-top height (m), and (e) CAPE (J/kg) during the period 2000-2014 in R2. Values of correlation coefficients (R) and significance level (p-value) 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. The table 1 presents the correlation coefficients between these parameters and the number of lightning flashes for 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 in summer, with R1 at -0.17 and R2 at -0.16. For 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), but presents a slight negative correlation in summer (-0.09). The ice cloud optical thickness in R1 maintains positive correlations across all seasons, peaking in summer (0.19), while R2 mostly mirrors this trend but includes 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 has mixed results with a high 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 weak 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 that cloud fraction and optical thickness of ice cloud are similar in both R1 and R2, indicating that aerosols do not largely affect these variables. However, AOD and cloud-top height are not the same (Figures 4a, d and 5a, d), which may be caused by different weather and landscape in the two regions. R1 is close to Iraq and Abu Ghoveyr desert, implying that may more dust, wildfires, and anthropogenic aerosols are expected than R2. R2 is near the sea, implying that sources of aerosols 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, the latitude/longitude distributions of AOD of BC, mineral dust, sea salt, and sulphate have been 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 region experiences more amount of dust comparing with R1 region, with the value of AOD of dust of 0.12 for R1 compared with 0.15 for R2. However, the R2 region is a coastal region but Figure 6c shows that R1 were affected by more amount of AOD with sea salt source during the studied period (0.005 for R1 compared with 0.004 for R2). Although, the coastal nature of the R2 region led to be influenced by more AOD with sulphate source (0.09 and 0.11 in R1 and R2, respectively; Figure 6d).

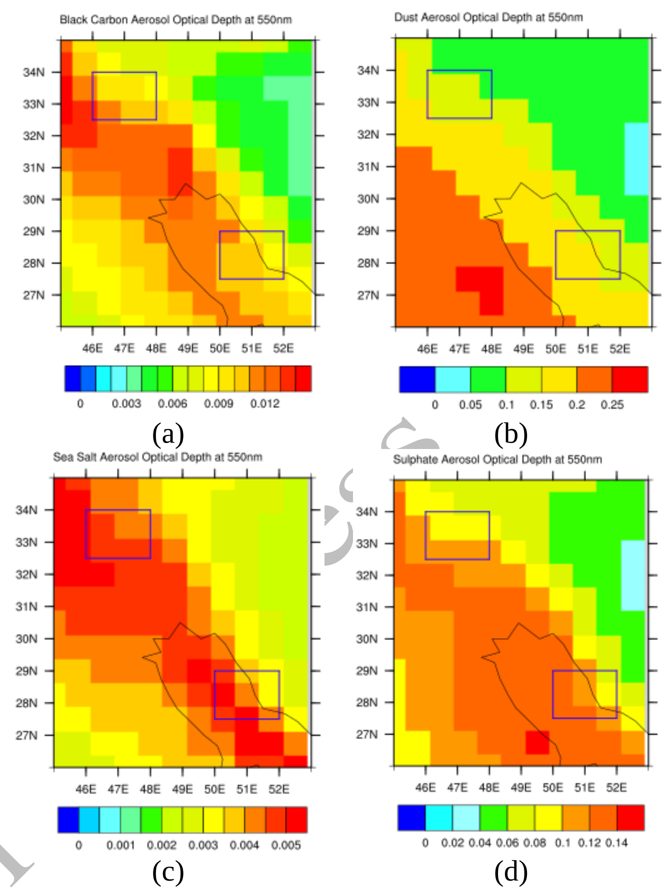
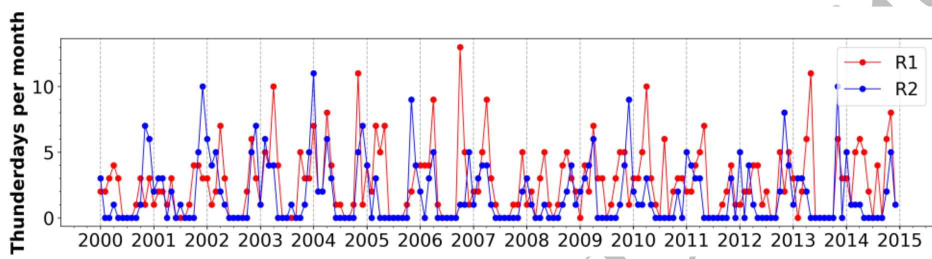


Figure 6. The horizontal patterns of averaged AOD for (a) BC, (b) mineral dust, (c) sea salt, and (d) sulphate from MACC reanalysis data during 2003 to 2012.

Figure 7 shows the number of lightning flashes and AOD in each day and month, and the number of thunder days in each month for the period 2000-2014. R1 and R2 experienced different electrical activity, but they happened at the same time 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 most lightning flashes in R1 and R2 were in 2006 and 2012, respectively. Rafati and Fattahi (2022) also found that lightning density is relatively higher in May and December in southwestern Iran for the period 1996-2014. Figure 7c-d shows daily and monthly variations of 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 may be affects the values of AOD in R1 because this region is characterized by a dry to semi-dry climate and is close to sources of dust 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 more abundant aerosols influence cloud development and the number of ice crystals, thereby contributing to more lightning. 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, which is defined as those days with at least one flash in a 24-hour period in each region (Figure 7h). Our analysis indicates that thunder days occur more often in both regions in April, May, October, and November same as results reported by Araghi et al. (2016) and Mojarrad et al. (2019) founding that thunderstorms mainly occurred during the cold months of the year (November to March), while in the warmer months (April to October).



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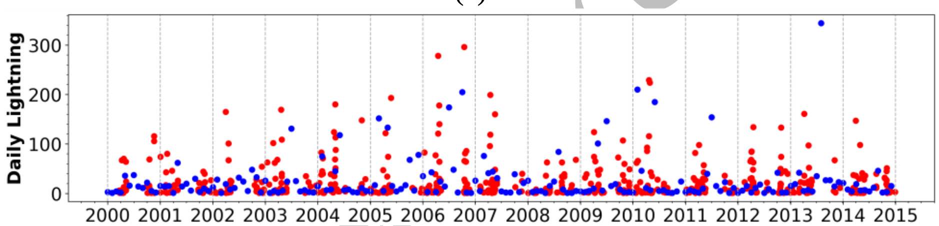

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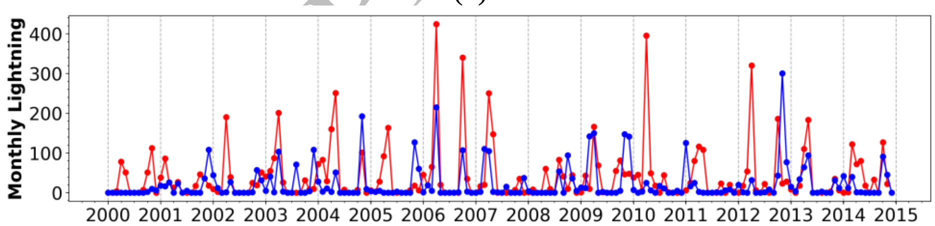
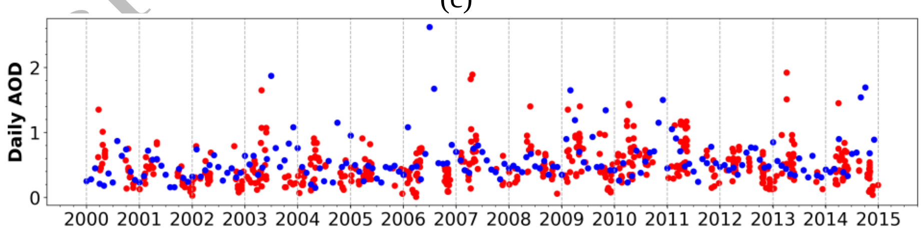
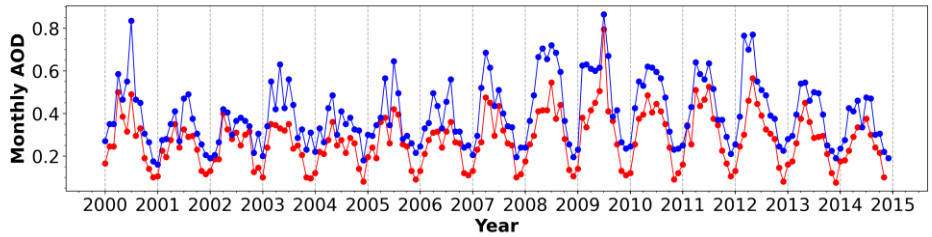


(c)



(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

We examined the impact of aerosols, thermodynamics and cloud characteristics on lightning in the western part of Iran during thunderstorm events from 2000 to 2014. We used the MODIS data, ERA5 data, and the LIS imaging sensor to extract cloud fraction, ice cloud optical thickness, cloud-top pressure and temperature, AOD, CAPE and lightning flash density during thunderstorm days in two different regions: R1 and R2. During the period 2000-2014, we identified 588 and 353 lightning days in R1 and R2, respectively.

The current 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 the presence of aerosols in the atmosphere not only influences cloud formation but also plays a significant role in enhancing the dynamics of storm systems. 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 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 analysis of CAPE 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).
Overall, 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. Supporting this conclusion, Zhao et al. (2020) emphasized that aerosol loading affects lightning in plateau and basin regions differently, altering convective activity and lightning density.

This research contributes to the broader understanding of how atmospheric conditions, particularly in arid and semi-arid regions, can outline 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 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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