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Influence of Aerosols on Lightning Activities in Java Island, Indonesia

Ahmad Rizqy Shubri, Mutya Vonnisa* and Marzuki Marzuki

Department of Physics, Universitas Andalas, Padang 25163, Indonesia

(*Corresponding author's e-mail: mutyavonnisa@sci.unand.ac.id)

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Abstract

Lightning is one of the natural disasters that cause significant financial losses and even fatalities. Therefore, it is necessary to understand the characteristics of lightning and related factors take appropriate preventive and mitigation measures. This work investigated the influence of aerosols and atmospheric thermodynamic factors on lightning in Java Island using 16 years of data (1998 - 2013) from the Tropical Rainfall Measuring Mission (TRMM) satellite. Aerosol data were obtained from the Modern Era Retrospective Analysis for Research and Applications version 2 (MERRA-2). Furthermore, convective available potential energy (CAPE) and potential temperature data were taken from the fifth-generation ECMWF atmospheric reanalysis (ERA-5) data. The intensity of lightning strikes in the western part of Java, such as Jakarta and Banten, is higher than in the eastern part, corresponding to the distribution pattern of aerosols, especially sulfate aerosols, sea salt aerosols, and black carbon aerosols. Sea salt aerosols have an inverse relationship with lightning, as these coarse-sized aerosols tend to inhibit convection. An increase in CAPE and potential temperature generally leads to higher lightning intensity. However, in cases where CAPE values are extremely high, such as in Jakarta, the intensity of lightning decreases. A similar pattern can be observed with potential temperature. An inverse relationship between lightning and potential temperature is observed in regions at higher elevations. The peak time for CAPE and potential temperature coincide with the peak intensity of lightning, which typically occurs during the rainy season, while the peak of AOD occurs earlier, during the pre-monsoon (September-October-November). The highest values of sea salt AOD are observed during the dry season (June-July-August) when lightning is minimal. These variations in peak times are particularly evident in the western regions of Java, where AOD values are high. The findings of this study can aid in lightning disaster mitigation efforts on Java Island.

Keywords: Java Island, Lightning, AOD, Aerosol, CAPE, Potential temperature

Introduction

Lightning is an atmospheric phenomenon that frequently accompanies rain events. It is generated by high voltage differences within thunderstorms, with currents reaching several hundred kiloamperes. Consequently, lightning, particularly Cloud to Ground (CG) lightning, can result in forest fires, environmental destruction, and fatalities [1,2]. Furthermore, lightning contributes to forming nitrogen oxides in the atmosphere and influences air quality [3,4].

Lightning is influenced by convective processes that are controlled by aerosols. Numerous studies have investigated the impact of aerosols on lightning [5,6]. High concentrations of aerosols can suppress the collision and coalescence processes of cloud droplets, thereby impeding warm rain formation [7,8]. Aerosols reduce the size of cloud droplets, resulting in decreased lightning intensity. Moreover, atmospheric aerosols play a critical role in organizing and consolidating convective clouds, leading to enhanced lightning activity in humid environments [9,10]. Strong and deep updrafts contribute to the formation of thunderstorms [10]. Increased aerosol concentrations have been reported in clouds with humidity exceeding 99 % [11]. The positive correlation between the effective radius of cloud droplets and aerosols is believed to be influenced by moisture effects [12].

The influence of aerosols on convective clouds and lightning activity is not determined solely by aerosol concentration but also by their type. The impact of aerosol concentration on lightning is nonlinear. When the Aerosol Optical Depth (AOD) is below 1.0, aerosols can enhance the occurrence of lightning [13]. However, above this threshold, lightning activity is hindered. Several studies indicate that high aerosol concentrations lead to the formation of small cloud droplets and can delay raindrop formation [7,8]. The influence of aerosol type on lightning also varies. Black carbon and sea salt aerosols affect atmospheric thermal stability, closely related to convection rates. Sulfate aerosols contribute to microphysical effects and can inhibit lightning activity through radiative effects [14]. Sulfate aerosol particles possess a significant ability to scatter solar radiation, leading to an increasing in the planet's albedo. As a consequence, these particles contribute to the cooling of the Earth's atmosphere and overall system [15].

In addition to aerosols, lightning is also related to local meteorological parameters that affect atmospheric thermodynamics, including the convective available potential energy (CAPE). CAPE controls the strength of updrafts, thereby influencing the intensity of lightning [16]. CAPE determines the atmospheric instability in moist convection [17,18], and it can serve as a proxy for lightning [18]. Previous studies have reported a positive correlation between lightning and CAPE [19,20]. Besides CAPE, surface temperature also influences lightning intensity. A positive correlation ($R \sim 0.66 - 0.69$) has been found between surface temperature and lightning in the Bay of Bengal and the Arabian Sea [8]. This positive relationship is attributed to the positive correlation between CAPE and surface temperature [21], with CAPE being the primary factor controlling the strength of updrafts in the formation of thunderstorm clouds that produce lightning.

Factors influencing lightning, such as aerosols, local meteorological parameters, and CAPE, vary across regions due to population density, economic activities, topography, vegetation, etc. In regions with complex topography, convective processes are affected by orographic lifting, which enhances CAPE and impacts lightning intensity, as observed in the northeastern Himalayan mountains [22]. Areas with high population density and intense economic activities often have higher aerosol concentrations than regions with lower population density, resulting in varying levels of lightning activity. Several other examples highlight the strong correlation between aerosol concentration and human activities. Thornton *et al.* [23], reported that ship-generated aerosols increase ocean lightning occurrence. A recent example is the decrease in aerosol levels during the COVID-19 pandemic, which reduced lightning intensity [24,25]. Therefore, the factors influencing lightning intensity differ across regions. Thus, it is essential to research these factors in more regions to comprehend the characteristics of lightning and the specific factors influencing it in each region.

In this study, we analyzed the influence of aerosols, CAPE, and temperature on lightning intensity in Java Island. Java is one of Indonesia's most densely populated islands, with a population of approximately 154.28 million people in 2022 [26]. Therefore, Java aerosols are predominantly anthropogenic from human activities [18]. Aerosols in Java contribute significantly to the overall aerosol levels in Indonesia, alongside Sumatra and Kalimantan Islands [27]. Lightning events in Indonesia have resulted in numerous casualties, with approximately 51 fatalities in 2017 [28]. Despite the significant impact of lightning-related disasters on Java Island, research on lightning characteristics in this region is still limited. Hence, this study is essential to mitigate lightning activities in this area.

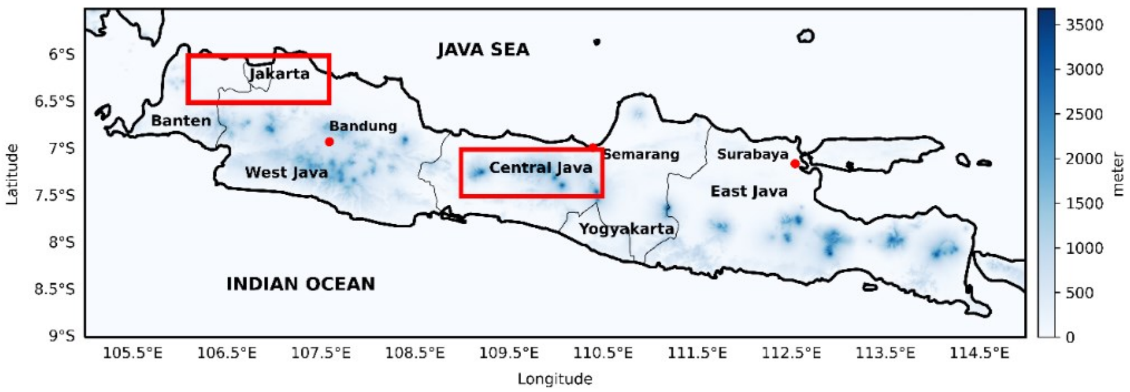

Figure 1 Topography map of the Java island. The red boxes indicate the 2 locations that will be analyzed to compare lightning in lowland (Jakarta) and highland (Central Java) areas.

Materials and methods

Study area

The research area is Java Island, between the Java Sea and the Indian Ocean. In Java, there is Jakarta, which is the capital of Indonesia. Several metropolitan cities such as Bandung, Semarang, Surabaya, Yogyakarta, and others are also on this island. The topography of Java Island is diverse, with the highest peak reaching approximately 3,676 m. The northern coast consists of lowlands, while the southern coast is predominantly mountainous and highlands (**Figure 1**). Geographically, Java Island is situated between 5.5°

- 9° S and 105° - 115° E. Its proximity to the equator results in relatively constant air temperatures throughout the year. Java Island has two seasons: The rainy and dry seasons, with a single peak for both the rainy and dry seasons. Monsoons influence these seasons. The wet northwest monsoon occurs from November to March (NDJFM), while the dry southeast monsoon occurs from May to September (MJJAS). The highest rainfall is observed from December to February [29-31]. Meanwhile, April and October are the transition period for the two monsoons [32].

Data

This study utilized monthly lightning data from the Tropical Rainfall Measuring Mission (TRMM) satellite. The data used in this study were gridded data processed by Albrecht *et al.* [33], with a resolution of 0.1°×0.1°. The available data used in this research span from January 1, 1998, to December 31, 2013 [33]. After this period, TRMM satellite data is no longer available. We also use Aerosol Optical Depth (AOD) data from MERRA-2 (Modern-Era Retrospective Analysis for Research and Applications, version 2). MERRA-2 provides AOD data for various aerosol types, such as total aerosols, black carbon (BC), sulfate, and sea salt, with a spatial resolution of 0.5°×0.625° [34,35]. The AOD data from MERRA-2 are primarily derived from the Moderate Resolution Imaging Spectroradiometer (MODIS), particularly after 2002, when data from the Terra and Aqua satellites became available [34].

Convective Available Potential Energy (CAPE) and potential temperature data were used to observe the thermodynamic factors. CAPE is the energy available in an air parcel and influences cloud formation processes. Moreover, potential temperature (θ) represents the temperature a parcel of air would have if adiabatically compressed from its current pressure and temperature to standard pressure (P). According to Stolz *et al.* [36], thermodynamic parameters such as CAPE and potential temperature determine lightning occurrence factors. This data was obtained from The European Centre for Medium-Range Weather Forecast (ECMWF) Reanalysis 5th Generation (ERA5) with a spatial resolution of 0.25°×0.25° and a temporal resolution of 1 h.

Methods

The study begins by calculating the value of potential temperature (θ) using the following equation:

$$\theta = T\left(\frac{1000}{P}\right)^{0.286} \quad (1)$$

where T and P denote surface temperature and pressure, respectively. Since the spatial resolution of the lightning data differs from the other datasets, an interpolation method is employed to match the spatial resolution of all the data. Qualitative analysis was first conducted by comparing the spatial distribution of lightning intensity, AOD, CAPE and potential temperature across Java Island. To quantitatively assess the relationship between lightning and AOD, CAPE, and potential temperature, linear regression of all grids of data was used. Then twgo regions on Java Island with different levels of AOD were identified, and their lightning intensities compared. In this case, the comparison was made between highland and lowland areas. The data was then averaged monthly to observe the monthly variation of each parameter. Finally, the distribution of correlation coefficients was calculated to see the influence of aerosols on lightning for each observation area.

Results and discussion

Spatial distribution of lightning, AOD and atmospheric thermodynamics in Java Island

Figure 2(a) shows the average annual lightning intensity per kilometer for the 16-year observation period (1998 - 2013). The lightning intensity in Java Island varies across different regions. Generally, the western regions of Java Island, such as Banten, Jakarta, and West Java Province, exhibit higher lightning intensity compared to the eastern regions. The highest lightning intensity is found at the border between DKI Jakarta and West Java Province (> 80 flashes/km^2 per year). The coastal areas in southern Java Island have the lowest lightning intensity (< 9 flashes/km^2 per year).

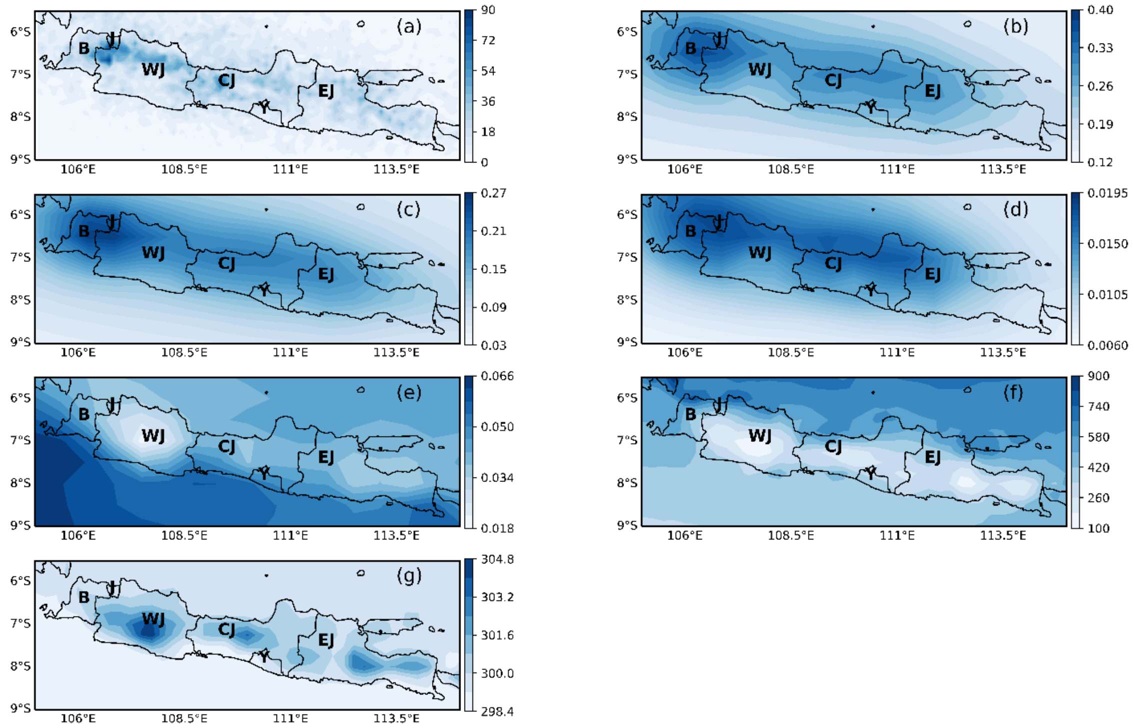

Figure 2 Spatial distribution of the average a) Lightning (flashes/km^2 per year), b) Total aerosol, c) Sulfate, d) Black carbon, e) Sea salt, f) CAPE (J/kg), and g) Potential temperature (K), during the period of 1998 - 2013 over the Java island. Provinces in Java are marked with the following abbreviations: B = Banten, CJ = Central Java, EJ = East Java, J = Jakarta, WJ = West Java and Y = Yogyakarta.

The spatial distribution of lightning is similar to that of Aerosol Optical Depth (AOD). Areas with high lightning intensity also show high AOD values, particularly in total AOD (**Figure 2(b)**), sulfate AOD (**Figure 2(c)**), and black carbon AOD (**Figure 2(d)**), indicating a positive relationship between aerosols and lightning in Java Island. This can be quantitatively determined from the regression coefficients between lightning and AOD, which are 0.84 for total aerosols, 0.89 for sulfate aerosols, and 0.77 for black carbon (**Figures 3(a) - 3(c)**). The aerosol with the highest AOD is the total aerosol, followed by sulfate aerosol, sea salt aerosol, and black carbon aerosol. The range of total aerosol AOD is between 0.14 and 0.37, with an average of 0.22, while sulfate aerosol AOD ranges from 0.05 to 0.26, with an average of 0.12. Sulfate aerosol is the dominant aerosol in Java Island, contributing 36 to 72 % of the total aerosol [27]. The AOD of black carbon aerosol ranges from 0.005 to 0.018, with an average of 0.01. Although the AOD of black carbon aerosol is relatively small, its influence on atmospheric heat structure cannot be ignored. It can absorb sunlight and act as a coagulation nucleus [37]. These 3 types of aerosols (total aerosol, sulfate, and black carbon) are significantly observed in the Jakarta and Banten regions, where lightning intensity is also high (**Figure 2(a)**). This is likely due to urban pollution resulting from human activities, especially industry [38]. In contrast to other aerosol types, which are dominant in urban areas, sea salt aerosol is mainly observed along the coastal areas (**Figure 2(d)**). The AOD of this aerosol ranges from 0.01 to 0.05, with an average of 0.03. The southern coastal region of Java Island has a higher concentration of sea salt aerosols compared to the northern coast, which is likely influenced by the monsoonal winds, particularly the east monsoon (May-September), passing through the southern coastal region of Java Island [39,40]. Winds aid in the formation of sea salt through wave breaking and bubble bursting, as well as its dispersion in the atmosphere [17]. Areas with high sea salt AOD have low lightning intensity, indicating an inverse relationship between sea salt aerosols and lightning. This is further confirmed by the correlation coefficient between lightning and sea salt AOD for all grid data, which is −0.52 (**Figure 3(d)**).

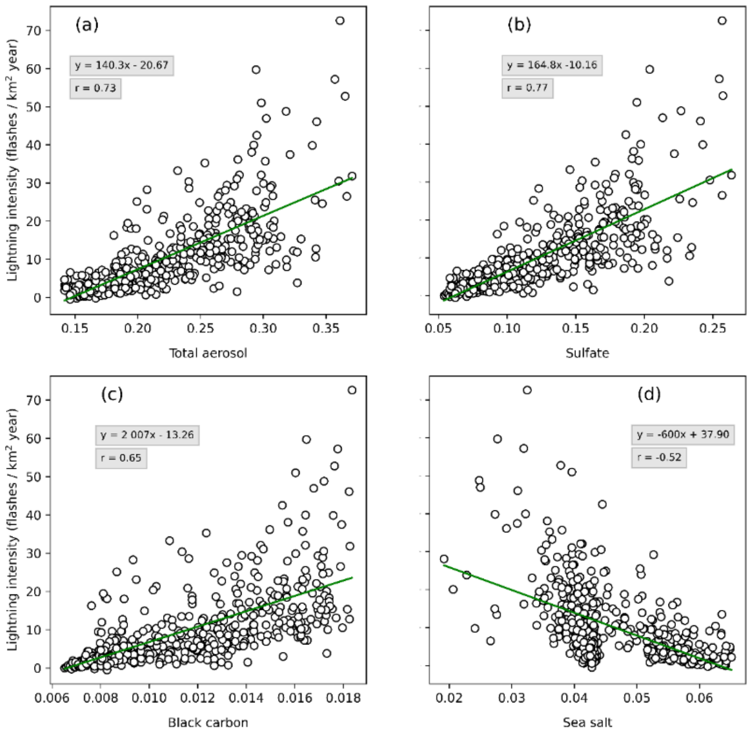

Figure 3 Scatter plot between lightning and AOD (Aerosol Optical Depth) for a) total aerosol, b) sulfate, c) black carbon, and d) sea salt, for all grid data in **Figure 2**.

Figure 2(f) shows the spatial distribution of Convective Available Potential Energy (CAPE) in Java Island. CAPE values range from 124.58 to 890.04 J/kg, with an average value of 465.16 J/kg. The coastal areas, especially the northern coast, have higher CAPE than the highlands. The northern coastal region also experiences relatively high lightning intensity, indicating the influence of CAPE on lightning in Java. CAPE can be used to identify atmospheric instability [41]. The higher the CAPE value, the greater the cloud formation and precipitation potential, resulting in increased rainfall. The northern coast of Java has higher CAPE values due to the higher average sea surface temperature in the Java Sea, as it is closer to the equator. Additionally, this is likely influenced by the monsoonal winds. During the wet northwest monsoon season (November-March), moist air from the Indian Ocean is pushed towards the northern coast of Java, leading to increased CAPE and rainfall in this region. Although a positive relationship between CAPE and lightning is observed on the northern coast of Java, an inverse relationship between lightning and CAPE is observed in the central inland of Java. The high lightning intensity in this area is associated with a relatively low CAPE. Thus, the influence of CAPE on lightning in Java Island exhibits regional variation. This is also evident from the small correlation coefficient between lightning and CAPE, which is −0.25 (**Figure 4(a)**).

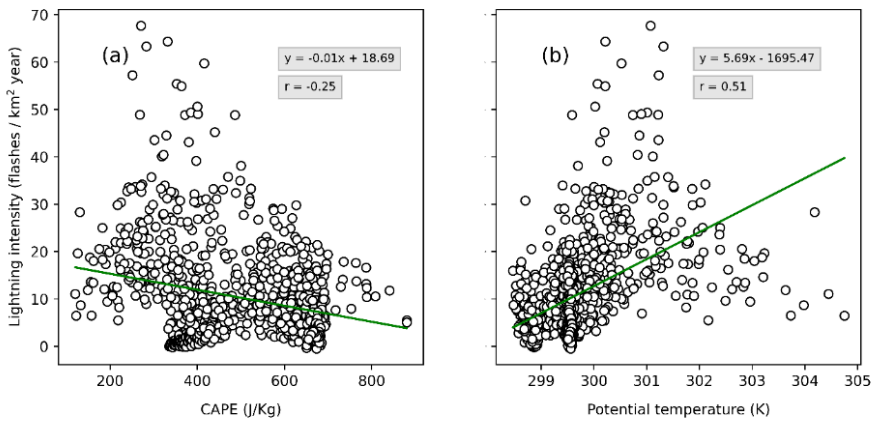

Figure 4 Scatter plot between lightning and a) CAPE and b) potential temperature, for all grid data in **Figure 2**.

Figure 2(g) shows the spatial distribution of potential temperature in Java Island. The potential temperature in Java ranges from 298.45 to 304.51 K, with an average of 299.6 K. The potential temperature values in highland areas, such as the mountainous regions of Java, are higher compared to the lowlands. This is due to the decrease in temperature and atmospheric pressure with increasing elevation. In general, the spatial distribution of potential temperature is similar to the distribution of lightning, indicating a positive relationship between lightning and potential temperature on the island of Java, except in specific areas such as the highlands of West Java. This positive relationship between potential temperature and lightning is further supported by the correlation coefficient, which is 0.51 (**Figure 4(b)**).

Comparison of lightning characteristics in the highlands and lowlands

There are 2 locations with different topographies but equally high lightning strikes, namely around DKI Jakarta (106.1° - 107.6° E; 6.5° - 6° S), which is a lowland, and Central Java (109° - 110.5° E; 7.5° - 7° S), which is a highland area (**Figure 2**). The average elevation of these two areas is 57.77 and 631 m, respectively. This subsection compares the relationship between lightning and AOD, CAPE, and potential temperature for these two regions.

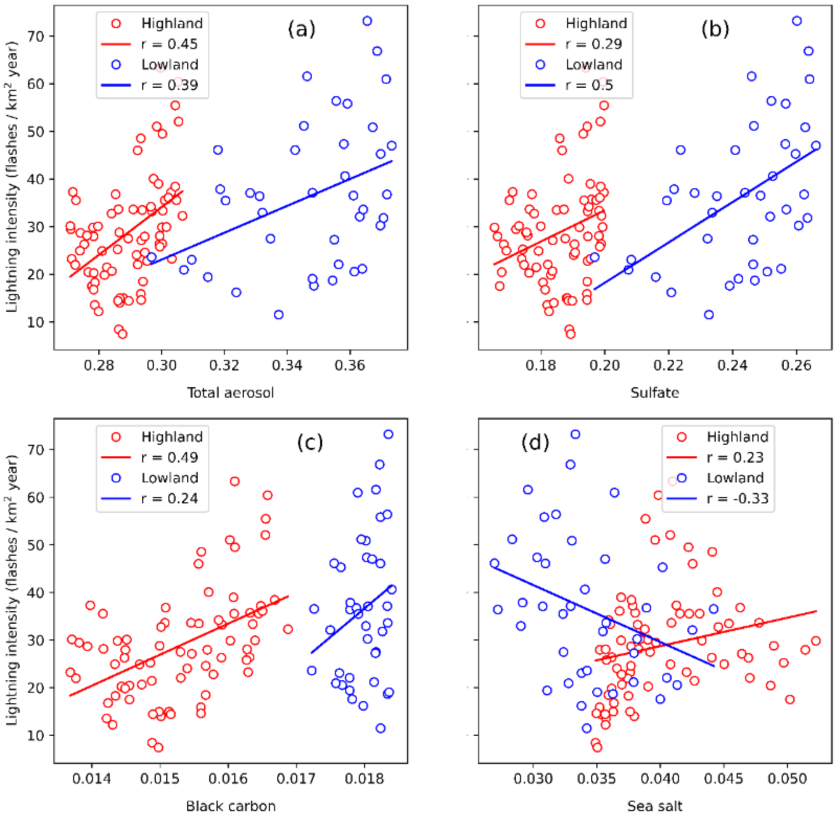

Figure 5 Scatter plot between lightning and AOD (Aerosol Optical Depth) for a) total aerosol, b) sulfate, c) black carbon, and d) sea salt, for all highland and lowland.

Figure 5 shows the relationship between lightning and AOD in highland and lowland areas. In the highland area, all aerosols have a positive relationship with lightning. This indicates that aerosols contribute to the growth of lightning activity. Aerosols can act as cloud condensation nuclei, reduce cloud droplet size, delay warm rain processes, and release significant latent heat, stabilizing the atmosphere [13]. However, not all aerosols have a positive relationship with lightning in the lowland area. The concentration of AOD in the lowland area (Jakarta) is higher than in the highland area (Central Java). In higher AOD (polluted areas), the radiative effect of aerosols plays a dominant role. Excessive aerosols can reduce atmospheric instability through radiation reflection [42]. This reduces the convective energy, inhibiting convection processes and the formation of thunderstorm clouds. The resistance effect of aerosols on lightning intensity is evident, especially for sea salt and black carbon aerosols [37,43].

CAPE and potential temperature in highland and lowland areas also show different impacts on lightning (**Figure 6**). In the highland area, CAPE and lightning have a positive relationship, while in the lowland area, they have an inverse relationship ($r = -0.79$). The highland area has low CAPE values, indicating weak convection. Weak convection forms positive lightning and environmental conditions that inhibit lightning growth [44]. The impact of potential temperature on lightning in highland and lowland areas is also different (**Figure 6(b)**). Potential temperature inhibits lightning activity in the highland area with a correlation coefficient reaching −0.31 (**Figure 6(b)**). If the potential temperature is high, the atmosphere becomes more stable, reducing the likelihood of air being lifted by topographic features and forming thunderstorm clouds or storms [41]. Therefore, in mountainous areas where the potential temperature is high, the occurrence of lightning may be less, resulting in a negative correlation between potential temperature and lightning. However, the opposite pattern occurs in the lowland area, with a correlation coefficient of 0.44 (**Figure 6(b)**). This is due to the increase in surface temperature caused by solar radiation, which enhances the instability of the boundary layer, aiding in the formation of convection and lightning [13].

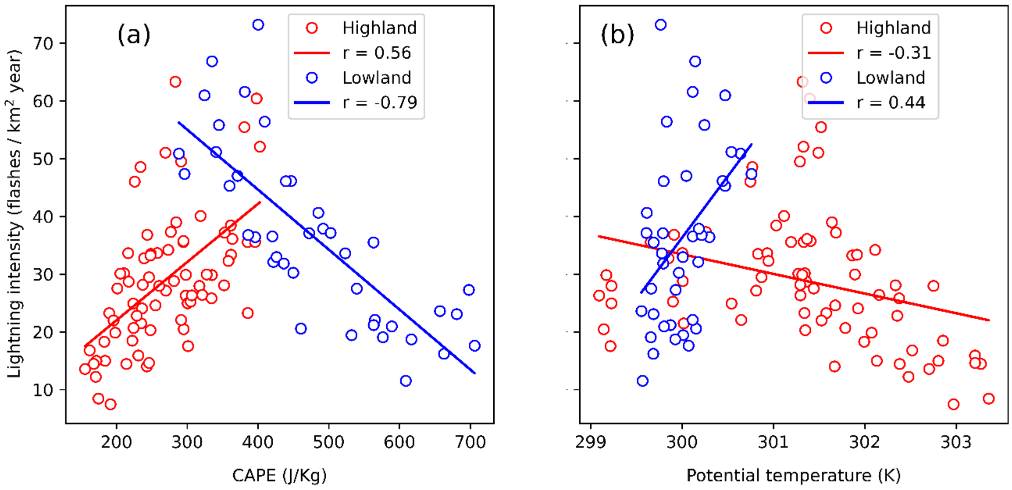

Figure 6 Scatter plot between lightning and a) CAPE and b) potential temperature, for highland and lowland.

Monthly variation of lightning intensity, AOD and atmospheric thermodynamics

In the above subsection, the spatial distribution of lightning was compared with AOD, CAPE, and potential temperature for the entire observation period. In this subsection, we discussed monthly variations to determine the peak time of each data. **Figure 7** shows the time series of monthly averaged AOD and lightning for all data in Java Island. The AOD of 3 types of aerosols (total, sulfate, and black carbon) exhibit the same monthly patterns as the lightning intensity (**Figures 7(a)** - **7(c)**, where both AOD and lightning show a dominant peak. However, the peaks of AOD and lightning occur) in different months. The peak time of lightning intensity was observed in December, January, and February (DJF), while the AOD peak occurs earlier in September, October, and November (SON). The peak time of lightning corresponds to the convective period in Java Island. The convective period usually occurs when the dominant winds blow eastward during DJF. AOD values decrease during DJF, which coincides with the peak time of the rainy season on Java Island [29]. Rainfall reduces the lifetime of aerosols in the atmosphere. Therefore, lightning is high in Java Island during the rainy season (DJF), while AOD is high during the pre-season (SON). This difference in peak time results in smaller correlation coefficients between lightning and AOD in **Figures 7(a)** - **7(c)** compared to climatological data in **Figure 2**, which are −0.02, 0.54, and 0.06 for total aerosols, sulfate, and black carbon, respectively. The difference in peak time between AOD and lightning has also been found in the Uttarakhand region, India.

Sea salt AOD shows an inverse relationship with lightning intensity, as also observed in **Figure 3**. The maximum AOD values are observed in June, July, and August (JJA), during which the lightning activity is minimal. JJA represents the dry season in Java Island with fewer convective clouds than in other months. During JJA, the monsoon winds blow from the south (Australia) towards the north (Indonesia). These winds carry limited moisture, producing less convective clouds over Java Island [39]. The reduced convective clouds subsequently lead to a decrease in the occurrence of lightning. However, these monsoon winds cause an increase in sea salt AOD during JJA (**Figure 7(d)**), especially in the southern coastal areas of Java (**Figure 2(e)**). This is why an inverse relationship between AOD and lightning intensity exists. The inverse relationship is also evident from the correlation coefficient value for the data in **Figure 7(d)**, which is −0.8.

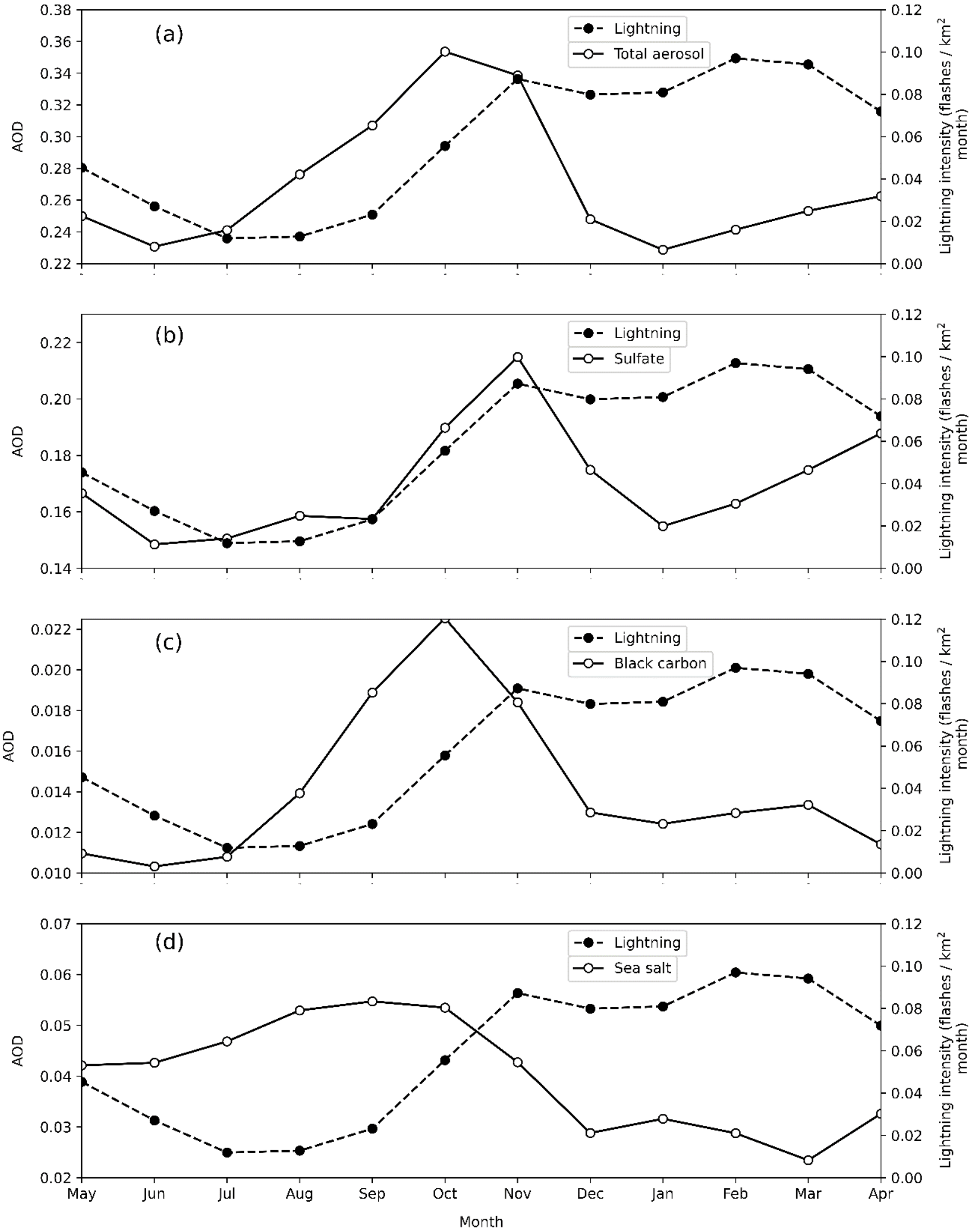

Figure 7 Monthly climatology for averaged values of AOD (on the primary Y-axis) with AOD (on the secondary Y-axis) for the period of 1998 - 2013 over the Java Island, for each type of aerosol.

The time series of atmospheric thermodynamic parameters resemble the time series of lightning intensity (**Figure 8**), and this is more evident in the case of CAPE than the potential temperature. The peak values of CAPE are nearly the same as the peak values of lightning intensity, while the peak values of potential temperature show some differences in April and May. The linear regression coefficients between CAPE and potential temperature with lightning are 0.92 and 0.71, respectively. Therefore, regarding monthly variations, CAPE exhibits a stronger positive relationship with lightning than potential temperature. The similarity in peak timing between AOD, CAPE, and potential temperature is also observed in the Uttarakhand region, India [22].

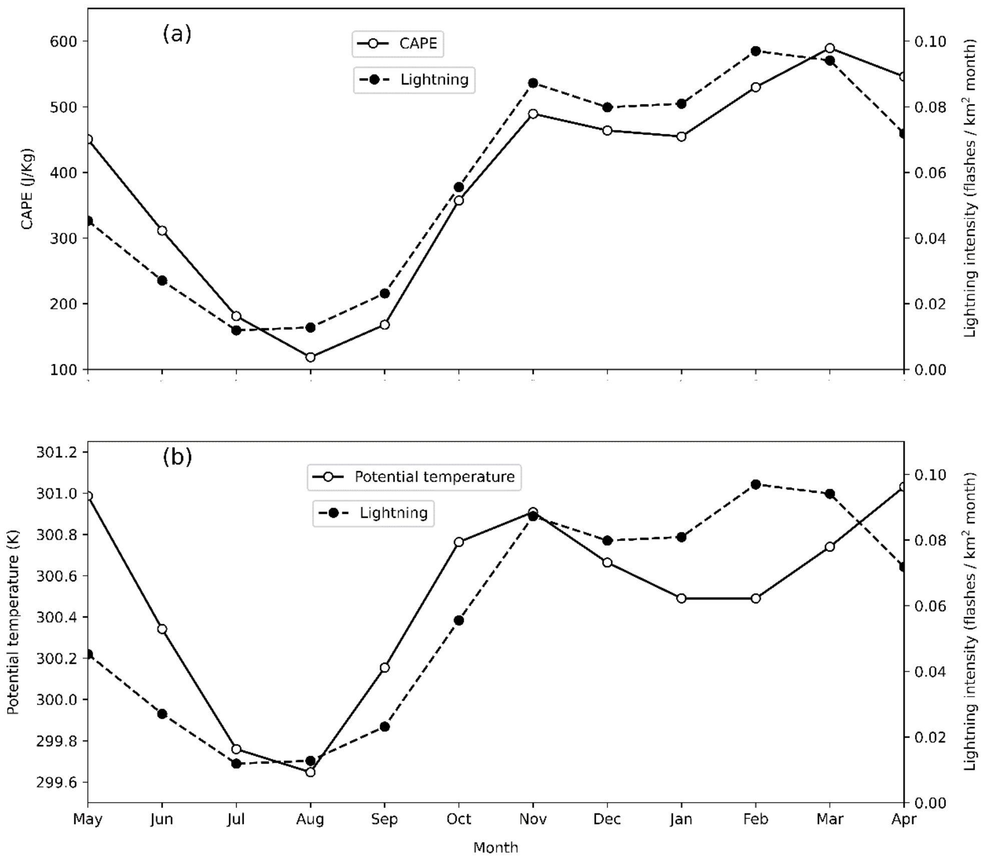

Figure 8 Monthly climatology for averaged values of CAPE and potential temperature (on the primary Y-axis) with lightning intensity (on the secondary Y-axis) for the period of 1998 - 2013 over the Java Island.

The monthly regression coefficients for each grid are analyzed to examine the regional variation of the monthly relationship between lightning and AOD, CAPE, and potential temperature (**Figure 9**). Generally, in the eastern part of Java Island, the regression coefficients for total aerosol, sulfate, and black carbon are higher than in the western part. In **Figure 2**, the eastern part of Java Island has lower AOD values than the western part. The air in the eastern part is still considered clean because the AOD values are < 0.2 [45]. The high correlation is likely due to the low temporal variation of lightning and aerosol in this region because of their small values. Higher lightning activity is observed in polluted areas with AOD > 0.2 [46,47]. Aerosol-cloud interactions generate lightning in areas with low AOD values, while for higher AOD values, the radiation effect of aerosol plays an essential role in initiating lightning [48]. The lower correlation between AOD and lightning in the western part of Java Island indicates a difference in lightning peaks in this region compared to AOD. The increase in lightning intensity in this area is likely observed during the pre-monsoon and post-monsoon periods, as seen in **Figure 7**, with AOD values around 0.2 - 0.4 (**Figures 2(b)** - **2(d)**), indicating that anthropogenic emissions dominate aerosols [45]. The regional variation for sea salt aerosol is unclear (**Figure 9(d)**), as almost all parts of Java Island show negative values, indicating an opposite peak timing between AOD and lightning, as seen in **Figure** 7(**d)**.

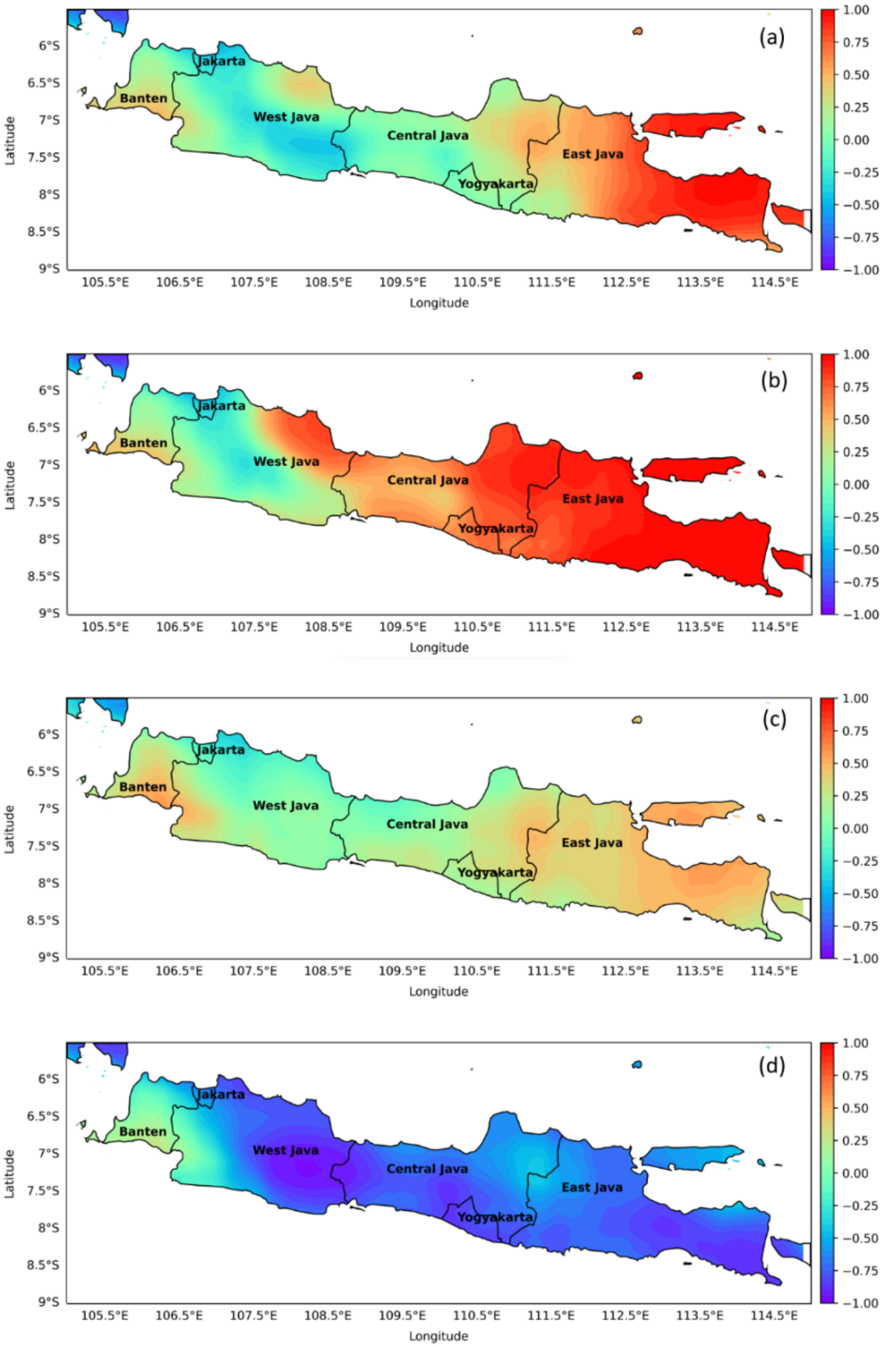

Figure 9 Spatial distribution of the correlation coefficient on monthly basis between lightning intensity and AOD a) Total aerosol, b) Sulfate, c) Black carbon, and d) Sea salt.

Conclusions

This study's result shows that the lightning intensity in Java Island depends on AOD, CAPE, potential temperature, and topography. Generally, areas with high lightning intensity tend to have high AOD values, especially in total aerosols, sulfates, and black carbon. Positive relationships were observed in all regions, both highland and lowland areas. Dominant aerosol AOD from sea salt was observed in the southern regions of Java Island and had a negative relationship with lightning intensity. These research findings are consistent with the characteristics of aerosols concerning cloud electrification. Fine aerosols such as sulfates and black carbon enhance cloud electrification, while coarse aerosols from sea spray weaken lightning by weakening convection within clouds. The influence of CAPE and potential temperature on lightning depends on topography. Generally, an increase in CAPE and potential temperature will increase the lightning intensity, but when CAPE values are very high, lightning intensity decreases, as observed in Jakarta. The same pattern applies to potential temperature, where in highland areas, which typically have high potential temperature values, there is an inverse relationship between lightning and potential temperature. CAPE and potential temperature show the same peak time as lightning intensity during the rainy season. However, aerosols show a different peak time. Sea salt AOD exhibits an inverse relationship with lightning intensity, where the maximum AOD value is observed during the JJA months when lightning activity is minimal. This indicates the significant influence of monsoonal winds blowing from the south (Australia) to the north (Indonesia) in increasing sea salt AOD. Three types of aerosols (total, sulfates, and black carbon) show different peak times compared to lightning. Lightning intensity peaks during the rainy season (DJF), while AOD peaks appear earlier during the transitional season (SON). This difference in peak times is evident in the western regions of Java Island, where higher AOD values are observed. These research findings will enhance our understanding of lightning characteristics in Java Island, which is useful for lightning disaster mitigation. To determine the sources of aerosols in Java Island, in addition to AOD values, the Ångström exponent values will also be analyzed in future studies. Additionally, the results of this study are likely influenced by atmospheric variability, mainly diurnal variations related to changes in solar radiation, which are significant in Indonesia [49]. Therefore, the diurnal variations of lightning over the Java region and its relationship with aerosols are currently being investigated and will be published in a separate article.

Acknowledgements

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