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Research Article

Spatial Analysis of Aerosol Optical Depth in Western Java Indonesia

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Abstract: Air quality in Western Java is highly dynamic and shaped by environmental changes influenced by intense human activities. Aerosols—tiny particulate matter that affects air quality, weather, and climate—can be quantified using Aerosol Optical Depth (AOD), which measures aerosol concentrations in the atmospheric column. This research uses spatial regression analysis to examine the spatial distribution of AOD from GEE's platform (Google Earth Engine) and its relationship with rainfall and wind patterns during both the wet and dry seasons. The findings indicate that wind speed does not significantly impact AOD values, but wind direction does affect the distribution of rainfall and AOD, likely due to the monsoon system. During the wet season (December to March), high-intensity and widespread rainfall effectively cleanses the atmosphere of aerosols, leading to no significant effect on AOD (p-value > 0.05). In contrast, during the dry season, rainfall significantly influences AOD spatial patterns (p-value < 0.05). These results highlight the intricate interplay between meteorological factors and aerosol's behavior, emphasizing the seasonal variability in their interactions.

Keywords: Environmental Monitoring, Particulate Matter, Precipitation, Wind Speed.

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1. Introduction

Environmental changes driven by human activities significantly influence air quality, posing challenges for sustainable development. Indicators such as air quality levels are pivotal in shaping policies and strategies for sustainability in industrial, logistics, and mobility sectors [1]. Anthropogenic activities contribute substantially to air and water pollution, as well as climate change [2]. The Western Java region, including Jakarta, serves as Indonesia's hub for government and commerce, characterized by intense transportation and industrial activities. Jakarta, the world's tenth most populous city, faces severe air pollution linked to energy use in transport, domestic, and industrial sectors. Air pollution along major roads frequently reaches hazardous levels, with meteorological conditions exacerbating pollution episodes[3]. Other areas in Western Java, such as Tangerang in Banten Province and industrial zones in West Java like Bandung Regency, also experience high pollutant concentrations, often exceeding ambient air quality standards [4]. These challenges underscore the urgency of studying aerosol-related air pollution in Western Java to inform environmental management and policy-making.

Aerosols significantly influence atmospheric systems through direct, semi-direct, and indirect effects. The direct effect involves interactions between aerosols and radiation, stabilizing the planetary boundary layer and exacerbating air pollution [5]. Indirectly, aerosols act as cloud condensation nuclei or ice nuclei, affecting cloud microphysics and precipitation patterns. While moderate aerosol loading can enhance precipitation, excessive concentrations reduce precipitation efficiency. Feedback mechanisms, including boundary layer and radiative interactions, are crucial in governing these dynamics [6]. Aerosols also modulate meteorological systems, suppressing large-scale precipitation from shallow clouds while intensifying deep convection, potentially causing catastrophic floods in localized areas. High-impact weather events such as tornadoes and tropical cyclones are closely associated with aerosol concentration and distribution. Additionally, the interplay between aerosols and boundary layer meteorology significantly contributes to urban haze pollution [7].

Meteorological factors, particularly wind dynamics, play a critical role in shaping aerosol behavior. Increased wind speed introduces larger particles into the atmosphere, as indicated by the anti-correlation between wind speed and the Ångström exponent, primarily affecting coarse aerosol fractions [8]. Local wind direction also emerges as a significant factor in aerosol particle distribution [9], emphasizing the complex interactions between aerosols and meteorology.

AOD is a critical measure of atmospheric aerosols, defined as the dimensionless integral of particle number concentration and extinction cross-section along a vertical path. Factors such as particle size, composition, and structure determine aerosols' interactions with radiant energy, influencing the Earth's heat balance [10]. As a widely recognized indicator for atmospheric physics and air quality, AOD is primarily monitored using satellite-based observations, offering large-scale insights into aerosol dynamics [11]. The use of geospatial platforms like Google Earth Engine (GEE) enhances the analysis and visualization of satellite-based pollutant and meteorological data, supporting precise regional air quality assessments [12].

Seasonal variations in AOD have been observed, with spatial and temporal differences influenced by meteorological factors. For instance, in Lanzhou City, AOD levels peak in spring and vary across regions, with precipitation reducing AOD in the eastern areas and wind speed positively influencing AOD in the western and eastern parts[13]. While precipitation typically scours aerosols, interactions between aerosols and precipitation are complex. Increased aerosol optical thickness can inhibit light rain but enhance convective precipitation, leading to heavier rainfall events, as observed in northern China[14]. The interplay between AOD and precipitation also varies regionally, with both positive and negative correlations identified across different areas in India [15]. Despite global advancements in understanding these dynamics, research on AOD and its interactions with meteorological factors remains limited in Indonesia. Recent studies in West Java aim to address this gap, analyzing AOD distribution and its relationship with rainfall and wind patterns. Such investigations are crucial for developing effective air quality management strategies that consider regional atmospheric conditions

2. Research Method

Study Area

The study area for this research is the Western Java region in 2023. The Western Java region includes three provinces: West Java Province, Jakarta, and Banten Province (Figure 1). Astronomically, West Java Province is located at 6°12' S and 106°48' E. Jakarta is situated between Banten and West Java Provinces, located at 6°12' S and 106°48' E. Meanwhile, Banten Province is astronomically located between 105°1'11" - 106°7'12" E and 5°7'50" - 7°1'1" S [16], [17], [18].

Figure 1. Map of the Study Area in Western Java

Tools and Materials

AOD data were obtained from MODIS (Moderate Resolution Imaging Spectroradiometer) satellite imagery. Meteorological data, including rainfall and wind patterns, were sourced from BMKG (Indonesian Meteorological, Climatological, and Geophysical Agency). The tools used in this study include a laptop with the software ArcMap 10.8, Google Earth Engine (GEE), and Microsoft 365. The materials used consist of data presented in Table 1.

Table 1: Research Data Specifications

Data	Temporal Resolution	Spatial Resolution	Source
Rainfall 2023	Daily	0.05° × 0.05°	CHIRPS
Aerosol Optical Depth (AOD) 2023	Hourly	0.5° x 0.625°	MERRA-2 Single Level Reanalysis
Wind Direction and Speed 2023	Hourly	0.25° x 0.25°	ERA-5 Single Level Reanalysis

Data Analysis

Spatial Mapping

Spatial mapping is conducted to create visual representations of AOD parameters, rainfall, and surface wind to enhance understanding of distribution, patterns, and relationships based on parameter visualization. This process involves collecting data for each parameter, namely AOD MERRA-2 and CHIRPS rainfall, through Google Earth Engine (GEE) computation, and wind speed data from ERA-5 through Copernicus. The collected datasets are then processed by aggregating different temporal resolutions into monthly data by averaging each parameter. Subsequently, the spatial resolution data is re-gridded into a single grid size. Re-gridding is a process involving the interpolation of one grid with another to produce different spatial resolution sizes[19]. Each parameter's data is then clipped to trim the raster data based on the Western Java region using a shapefile (SHP). Subsequently, adjustments are made to standardize the value ranges of each variable to ensure that the displayed visualization has a single legend. The final step involves arranging the data into a more structured format like a conventional map.

Spatial Regression

Spatial regression is a statistical regression method commonly used in data with location effects, also known as spatial effects. The spatial effects analysis consists of spatial dependency and spatial heterogeneity [20]. Spatial dependency is the dependence between observation locations and other locations. Meanwhile, spatial heterogeneity refers to the variation between locations or the differences between one location and another. The general spatial regression model is described as follows [21]:

$$y=\varrho Wy+X\beta+u \quad (1)$$

Explanation:

y = vector of response variables of size n x 1

ϱ = spatial lag parameter coefficient of the response variable

W = spatial weight matrix of size n x n

X = predictor variable matrix of size n x (p+1)

β = vector of regression parameter coefficients of size (p+1) x 1

λ = spatial error parameter coefficient

u = error vector with spatial effects of size n x 1.

3. Result and Discussion

Spatial Analysis of AOD, Rainfall, and Surface Wind in Wet and Dry Seasons

The spatial analysis of Aerosol Optical Depth (AOD), rainfall, and surface wind patterns in West Java reveals intricate seasonal dynamics shaped by the interaction between monsoon circulations and local climatic conditions. AOD values exhibit distinct seasonal variations, with lower values observed during the rainy season (December–May), indicating a significant influence of wet deposition processes (Figure 2). The reduction in AOD during this period aligns with increased precipitation, soil moisture, and vegetation coverage, collectively contributing to the suppression of dust aerosol concentrations, as similarly observed in the Thar Desert [22].

Conversely, during the dry season (June–November), AOD increases and is concentrated in the western part of West Java, particularly in Banten and Jakarta (Figure 2). This pattern is closely related to the movement of the Australian Monsoon wind, which carries dry air masses from the Australian continent along with high concentrations of black carbon and sulfate aerosols produced by anthropogenic activities in the area[23]

The efficiency of aerosol removal through precipitation is primarily governed by wet scavenging processes, which are influenced more by precipitation frequency than by intensity [24]. This finding is consistent with studies demonstrating that the spatial distribution of aerosol wet deposition correlates more strongly with variations in light precipitation frequency rather than total precipitation amounts[25]. The reduced wet deposition observed in some cases leads to an increase in AOD, reinforcing the importance of consistent precipitation events for effective aerosol removal.

Additionally, multiple factors influence AOD distribution, including the initial concentration of aerosols, precipitation event duration, the time interval between successive rainfall events, and precipitation frequency [24], [26]. Seasonal transitions further contribute to AOD variability, as shifts in wind direction impact aerosol transport and accumulation patterns. These results highlight the complex interactions between meteorological parameters and aerosol dynamics in West Java.

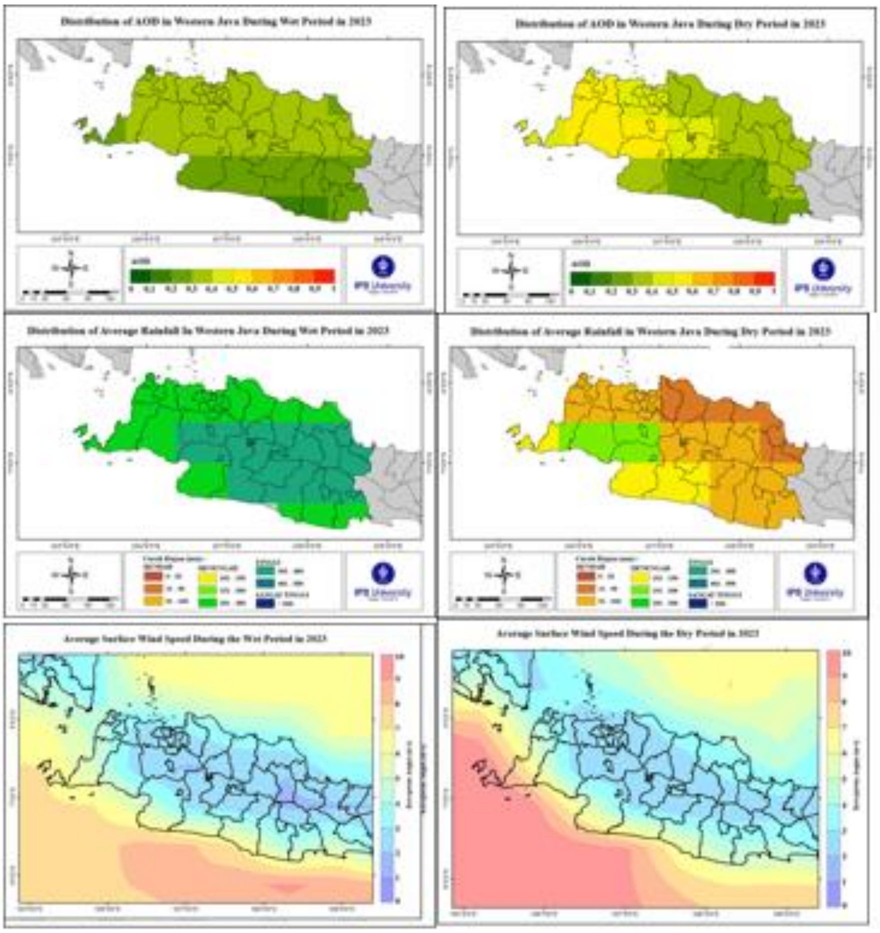


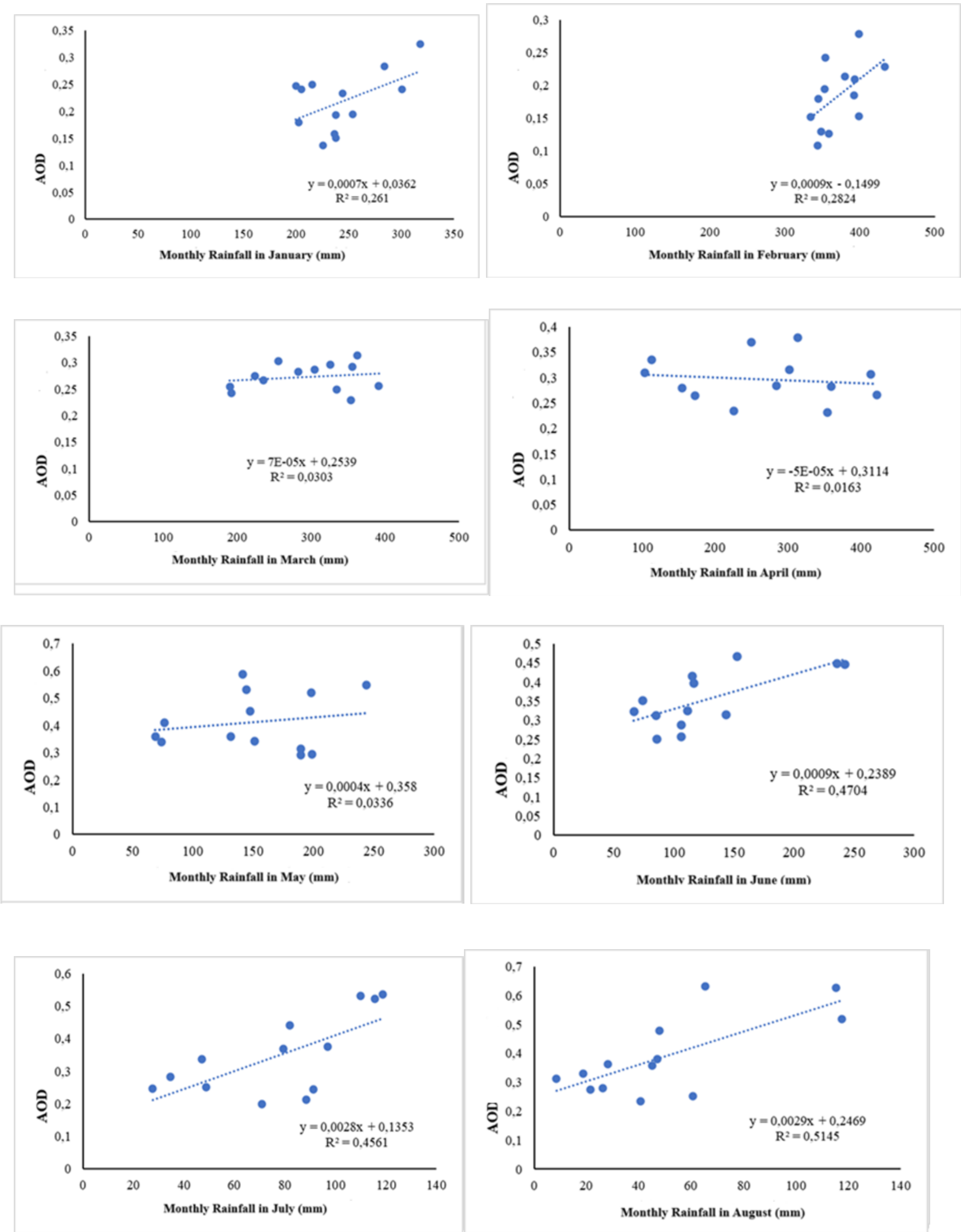
Figure 2 Maps of mean AOD (top), precipitation (middle), and mean wind speed (bottom) during the wet season (DJF-MAM period) and the dry season (JJA-SON period) in 2023.

The Relationship Between AOD, Rainfall, and Wind

The relationship between Aerosol Optical Depth (AOD) and rainfall exhibits a positive correlation in certain months; however, statistical analysis indicates that rainfall accounts for only a small fraction of AOD's spatial variability. This is evident from the relatively low coefficient of determination (R^2) values, which range between 0.01 and 0.28 during the rainy season and from 0.03 to 0.51 in the dry season (Figure 3). The efficiency of aerosol removal from the atmosphere is influenced by multiple factors beyond precipitation, including aerosol concentration before precipitation, event duration, and the interval between successive precipitation events [26].

Aerosol wet scavenging is more dependent on precipitation frequency rather than intensity, as evidenced by scavenging amount modes that are consistently lower than the rainfall amount mode associated with the highest accumulated precipitation [24]. This suggests that intermittent but frequent precipitation events play a more crucial role in aerosol removal than isolated high-intensity rainfall. Seasonal transitions further influence this relationship, as changes in wind direction during April–May and September–October lead to erratic rainfall distribution patterns, weakening the overall correlation between rainfall and AOD.

Although wet deposition remains a crucial mechanism for aerosol removal, the interaction between aerosols and atmospheric systems is highly complex. This complexity arises from the interplay of aerosol properties, such as size, composition, and vertical distribution, alongside meteorological factors, including wind speed, humidity, and temperature [27], [28]. These findings emphasize the necessity of a multifaceted approach to understanding aerosol dynamics beyond simple precipitation-based removal mechanisms.



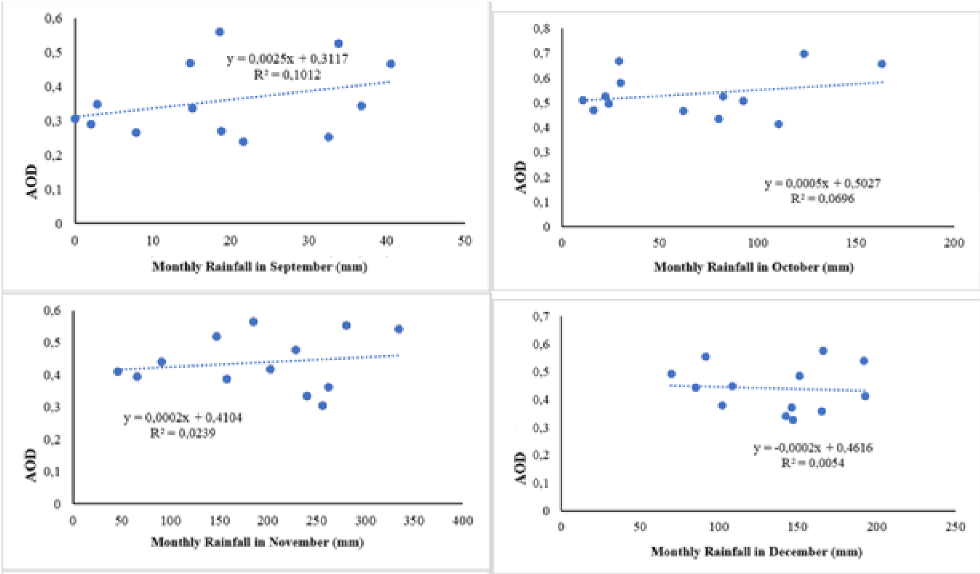


Figure 3 Correlation (Scatter plot) of spatial distribution of Rainfall and AOD from January to December

4. Conclusion

This study provides a comprehensive analysis of Aerosol Optical Depth (AOD) distribution and its relationship with rainfall and wind patterns in West Java. The results indicate that AOD exhibits distinct seasonal variations, with lower and more evenly distributed values during the rainy season and higher concentrations in the western region during the dry season. Wet deposition plays a crucial role in reducing aerosol concentrations; however, statistical analysis reveals that rainfall alone explains only a small portion of AOD's spatial variability, as reflected in the low R^2 values. The efficiency of aerosol removal is significantly influenced by precipitation frequency rather than intensity, highlighting the importance of consistent rainfall events over isolated heavy precipitation. Additionally, seasonal transitions and shifts in monsoon wind patterns further complicate the spatial distribution of AOD, particularly during April–May and September–October.

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