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Characterizing Aerosol Size Distributions, Fine Mode Aerosol Dominance, and Seasonal Aerosol Regimes over Penang, Malaysia Using AERONET SDA Retrievals.

By

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Abstract

Atmospheric aerosol size distributions play a critical role in determining aerosol radiative effects, air quality, and climate interactions. This study investigates aerosol size characteristics over Penang, Malaysia, using AERONET Version 3 Spectral Deconvolution Algorithm (SDA) Level 2.0 observations collected between 2018 and 2022. The analysis focused on Aerosol Optical Depth (AOD), Fine Mode Fraction (FMF, η), and Ångström Exponent (AE) to characterize temporal variability and aerosol regimes in a tropical coastal environment. Descriptive statistics showed mean values of 0.284 ± 0.210 for AOD, 0.713 ± 0.145 for FMF, and 1.251 ± 0.212 for AE, indicating persistent dominance of fine-mode aerosols. Monthly analysis revealed elevated aerosol loading during March–April and September, while AE and FMF remained consistently high throughout the year. Interannual distributions demonstrated relatively stable aerosol size characteristics during the study period, with median AE and FMF values remaining above 1.2 and 0.70, respectively. Aerosol regime classification indicated that mixed aerosols (47.89%) and fine-mode-dominated aerosols (45.05%) were the most frequently observed conditions, whereas coarse-mode aerosols accounted for only 7.05% of observations. A positive relationship between AE and FMF (R^2 = 0.421) confirmed the strong influence of fine particles on aerosol optical properties. Seasonal analyses further revealed enhanced fine-particle dominance during the inter-monsoon and Southwest Monsoon periods, while marine influences were more evident during the Northeast Monsoon. The findings demonstrate that aerosol characteristics over Penang are predominantly controlled by fine-mode particles originating from anthropogenic activities, secondary aerosol formation, and regional biomass-burning transport, providing valuable insight into aerosol variability within the Maritime Continent region..

Key Words- *Aerosol Optical Depth, Fine Mode Fraction, Ångström Exponent, Aerosol Regimes, Southeast Asia.*

Introduction

Atmospheric aerosols are among the most important components of the Earth–atmosphere system due to their significant impacts on climate, air quality, visibility, and human health [1–3]. Aerosol particles interact with incoming solar radiation through scattering and absorption processes and influence cloud formation by acting as cloud condensation nuclei, thereby affecting the Earth's radiative balance and hydrological cycle [1,2]. The magnitude of these impacts depends not only on aerosol concentration but also on particle size, composition, and optical properties. Consequently, understanding aerosol size characteristics is essential for evaluating aerosol–climate interactions and assessing environmental conditions in different geographical regions [4,5].

Aerosol particles are commonly classified into fine and coarse modes according to their size distributions and formation mechanisms. Fine-mode aerosols are generally associated with anthropogenic emissions, biomass burning, industrial activities, vehicular exhaust, and secondary aerosol formation processes, whereas coarse-mode aerosols are primarily generated through natural processes such as sea-salt production, mineral dust emissions, and mechanical resuspension [5]. Because fine and coarse particles exhibit distinct atmospheric lifetimes, transport pathways, and radiative effects, characterization of aerosol size distributions provides valuable information regarding aerosol sources and atmospheric processes [6].

Ground-based remote sensing observations have become an important tool for investigating aerosol optical and microphysical properties. The Aerosol Robotic Network (AERONET), established by NASA and PHOTONS, provides standardized, globally distributed observations of aerosol optical depth (AOD) and related aerosol properties with high accuracy and temporal resolution [7]. Continuous improvements in AERONET retrieval algorithms have enhanced the reliability of aerosol characterization and enabled long-term assessments of aerosol variability across diverse environments [8]. In particular, the Spectral Deconvolution Algorithm (SDA) developed for AERONET observations allows total aerosol optical depth to be separated into fine- and coarse-mode components, facilitating detailed analyses of aerosol size distributions and source influences [9].

Among the most widely used indicators of aerosol size characteristics are the Fine Mode Fraction (FMF) and the Ångström Exponent (AE). Fine Mode Fraction represents the contribution of fine particles to total aerosol optical depth and serves as an indicator of aerosol size dominance within the atmospheric column. Similarly, the Ångström Exponent provides information on particle size distribution, with larger values generally associated with fine particles and smaller values indicating coarse-particle dominance [10,11]. The combined use of FMF and AE has proven particularly effective for identifying aerosol regimes, distinguishing between anthropogenic and natural aerosol influences, and assessing temporal changes in aerosol populations [11,12].

Southeast Asia is recognized as one of the most aerosol-sensitive regions of the world due to rapid urbanization, industrial development, biomass-burning activities, and complex monsoonal circulation patterns [6]. Malaysia, located within the Maritime Continent, experiences seasonal variations in aerosol loading driven by the Northeast Monsoon, Southwest Monsoon, and two inter-monsoon periods. These seasonal meteorological conditions influence aerosol transport, accumulation, and removal processes, leading to substantial variability in aerosol optical properties throughout the year [10,12]. Penang, a rapidly developing coastal urban region situated along the Strait of Malacca, is particularly affected by a combination of local anthropogenic emissions, marine aerosols, and regionally transported particles. Understanding aerosol size characteristics in such environments is therefore important for improving regional air-quality assessments and climate studies.

Although previous studies have examined aerosol optical properties over Malaysia and other parts of Southeast Asia, relatively few investigations have focused specifically on long-term aerosol size regime characterization using AERONET SDA retrieval products [10,12,13]. Furthermore, information regarding the temporal variability of Fine Mode Fraction and its relationship with Ångström Exponent remains limited for tropical coastal environments such as Penang. Long-term assessments are necessary to identify dominant aerosol regimes, evaluate seasonal transitions, and improve understanding of aerosol source influences within the region.

Therefore, the objective of this study is to characterize aerosol size regimes over Penang, Malaysia, using AERONET Version 3 SDA Level 2.0 observations collected between 2018 and 2022. Specifically, the study investigates the temporal variability of aerosol optical depth, Fine Mode Fraction, and Ångström Exponent; examines seasonal and interannual changes in aerosol size characteristics; identifies dominant aerosol regimes; and evaluates the relationship between Fine Mode Fraction and Ångström Exponent. The findings provide new insights into aerosol size distributions within a tropical coastal environment and contribute to a better understanding of aerosol variability across Southeast Asia.

MATERIALS AND METHODS

A. Study Area

Penang is a rapidly urbanizing coastal region located in northwestern Peninsular Malaysia along the Strait of Malacca (5.36°N, 100.30°E). The region experiences a tropical climate characterized by relatively uniform temperatures throughout the year and seasonal variations associated with the Northeast Monsoon (December–February), Southwest Monsoon (June–August), and two inter-monsoon periods (March–May and September–November). Due to its strategic location, Penang is influenced by a combination of urban emissions, industrial activities, marine aerosols, and long-range transported particles from surrounding regions. These characteristics make the area suitable for investigating aerosol size distributions and aerosol regime variability within a tropical coastal environment.

B. SDA Dataset and Statistical Analysis

Daily aerosol observations were obtained from the Universiti Sains Malaysia (USM) Penang station of the Aerosol Robotic Network (AERONET). The study utilized Version 3 Spectral Deconvolution Algorithm (SDA) Level 2.0 retrieval products covering the period from January 2018 to December 2022. Level 2.0 data are automatically cloud-screened and quality-assured using pre-field and post-field calibration procedures, ensuring high-quality aerosol observations.

The analysis focused on three primary aerosol parameters:

1. Total Aerosol Optical Depth (τa) at 500 nm,
2. Fine Mode Fraction (η), and
3. Ångström Exponent (AE).

The dataset consisted of 950 daily observations distributed across the five-year study period.

Aerosol Optical Depth (AOD) represents the integrated attenuation of solar radiation by aerosol particles within the atmospheric column and provides a measure of aerosol loading.

The Fine Mode Fraction (η) describes the relative contribution of fine-mode aerosols to total aerosol optical depth and is expressed as:

$$\eta = \frac{\tau_f}{\tau_a} \quad , \qquad (1)$$

where:

η = Fine Mode Fraction,
τ_f = Fine-mode aerosol optical depth, and
τ_a = Total aerosol optical depth.

Values of η approaching unity indicate strong dominance of fine particles, whereas lower values indicate increasing contributions from coarse aerosols..

The Ångström Exponent (AE) is widely used as an indicator of aerosol particle size. Higher AE values generally correspond to fine-mode aerosols, while lower values indicate dominance of coarse particles. In this study, AE values derived from the SDA product were used directly for aerosol size characterization.

Aerosol regimes were identified using combined Fine Mode Fraction and Ångström Exponent characteristics. Following commonly applied aerosol classification approaches, three aerosol regimes were defined:
Fine-mode dominated aerosols:
AE > 1.2 and $\eta > 0.70$
Coarse-mode dominated aerosols:
AE < 1.0 and $\eta < 0.50$

Mixed aerosols:
All remaining observations (4)

This classification enables differentiation between aerosol populations dominated by anthropogenic and combustion-related particles and those influenced primarily by natural coarse particles such as sea salt and dust.

Descriptive statistics including mean, standard deviation, minimum, and maximum values were calculated for all aerosol parameters. Monthly, seasonal, and interannual variations were examined to evaluate temporal changes in aerosol size characteristics.

The relationship between Fine Mode Fraction and Ångström Exponent was evaluated using Pearson's correlation coefficient:

$$FC = \frac{\tau_f}{\tau_a} \times 100, \qquad (2)$$

Similarly, the coarse-mode contribution was determined as:

$$CC = \frac{\tau_c}{\tau_a} \times 100, \qquad (3)$$

These metrics provide quantitative measures of aerosol partitioning and facilitate the identification of dominant aerosol modes over Penang. Monthly climatological averages were calculated to evaluate intra-annual variability, whereas annual averages were used to examine interannual changes in aerosol characteristics during the study period.

To investigate seasonal aerosol variability, the observations were classified according to the prevailing monsoonal periods in Malaysia. The Northeast Monsoon (NEM) was defined as December–February, the First Inter-monsoon (IM1) as March–April, the Southwest Monsoon (SWM) as June–August, and the Second Inter-monsoon (IM2) as May and September–November. Seasonal averages of τ_a, τ_f, τ_c, FC, and CC were subsequently calculated and compared to assess changes in aerosol partitioning under different atmospheric circulation regimes.

Descriptive statistical analyses were performed to characterize the temporal variability of aerosol optical properties during the study period. The mean, standard deviation, minimum, and maximum values of τ_a, τ_f, τ_c, FC, and CC were calculated.

The relationship between fine-mode and coarse-mode aerosol optical depths was evaluated using Pearson's correlation coefficient (r), expressed as:

$$r = \frac{\sum_{i=1}^{n}(x_i-\bar{x})(y_i-\bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i-\bar{x})^2}\sqrt{\sum_{i=1}^{n}(y_i-\bar{y})^2}}, \qquad (3)$$

where (x_i) and (y_i) represent paired aerosol observations, $(\bar{x})$ and $(\bar{y})$ denote their respective means, and (n) is the total number of observations.

Positive values of r indicate that increases in Fine Mode Fraction are associated with increasing Ångström Exponent values, whereas negative values indicate an inverse relationship.

RESULT AND DISCUSSION

A. Descriptive Statistics of Aerosol Size Indicators

Table 1 summarizes the descriptive statistics of aerosol optical depth (AOD), Fine Mode Fraction (FMF), and Ångström Exponent (AE) derived from AERONET SDA observations over Penang during the period 2018–2022. These parameters provide important information regarding aerosol loading and particle size characteristics within the atmospheric column.

Table 1. Descriptive statistics of aerosol optical depth (AOD), Fine Mode Fraction (FMF, η), and Ångström Exponent (AE) over Penang, Malaysia during 2018–2022 based on AERONET Version 3 SDA Level 2.0 observations.

	Mean	Std	Min	Max
AOD	0.283863	0.210308	0.04139	2.614594
FMF	0.713152	0.144915	0.165913	0.985267
AE	1.250518	0.211983	0.225606	1.769186

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The mean AOD was 0.284 ± 0.210, indicating moderate aerosol loading over the study area. The observed AOD values ranged from 0.041 to 2.615, demonstrating substantial temporal variability in aerosol concentrations. The occurrence of high AOD events suggests episodic periods of enhanced aerosol accumulation associated with regional transport, biomass-burning influence, or local anthropogenic emissions. Similar ranges of aerosol optical depth have been reported for urban and coastal locations across Southeast Asia, where aerosol loading is influenced by both local emissions and transboundary transport processes [14].

The mean FMF was 0.713 ± 0.145, indicating that approximately 71% of the total aerosol optical depth was contributed by fine-mode particles. The predominance of fine particles suggests a strong influence of anthropogenic aerosols, secondary aerosol formation, and combustion-related emissions within the region. The FMF values varied from 0.166 to 0.985, indicating the presence of both coarse-particle-dominated and strongly fine-particle-dominated atmospheric conditions. The high average FMF observed in this study is consistent with previous investigations conducted in urban and maritime regions of Southeast Asia, where fine-mode aerosols commonly dominate atmospheric aerosol populations [11,15].

The mean AE value was 1.251 ± 0.212, with observed values ranging from 0.226 to 1.769. Since AE values greater than approximately 1.0 are generally associated with fine particles, the average AE further confirms the dominance of fine-mode aerosols over Penang during the study period. The broad AE range indicates substantial variability in aerosol size distributions, reflecting changing contributions from anthropogenic emissions, marine aerosols, and regional transport events. Elevated AE values approaching 1.8 correspond to periods dominated by fine particles, whereas lower values indicate increased influence of coarse aerosols such as sea salt and mechanically generated particles [10].

The combined FMF and AE statistics consistently indicate that the aerosol environment over Penang was predominantly characterized by fine-mode particles throughout the study period. The agreement between these two independent aerosol size indicators strengthens the interpretation that anthropogenic and combustion-related aerosols constitute a major component of atmospheric aerosol loading in this tropical coastal environment. These findings provide the basis for the subsequent examination of monthly, seasonal, and interannual aerosol size variability.

B. Monthly Variability of Aerosol Size Characteristics

Figure 1 illustrates the monthly variability of aerosol optical depth (AOD), Ångström Exponent (AE), and Fine Mode Fraction (η) over Penang during the 2018–2022 study period. Distinct seasonal patterns are evident in all three parameters, reflecting the influence of regional meteorology, aerosol emissions, and atmospheric transport processes on aerosol size distributions..

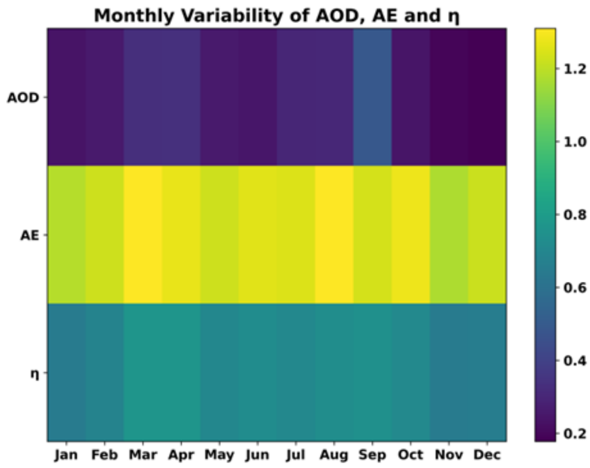

Figure 1.Monthly variability of Aerosol Optical Depth (AOD), Ångström Exponent (AE), and Fine Mode Fraction (η) over Penang, Malaysia.

The monthly AOD values exhibited considerable variability throughout the year, with elevated aerosol loading occurring during March–April and a pronounced maximum in September. The September peak corresponds to the highest monthly aerosol loading observed during the study period and likely reflects enhanced regional biomass-burning emissions and transboundary haze transport commonly affecting the Maritime Continent during the late Southwest Monsoon period [16]. In contrast, the lowest AOD values occurred during November and December, indicating cleaner atmospheric conditions associated with increased precipitation and more efficient aerosol removal during the Northeast Monsoon season [17].

The Ångström Exponent remained consistently above 1.0 throughout the year, with values generally ranging between approximately 1.15 and 1.30. The highest AE values were observed during March, April, August, and October, indicating increased dominance of fine-mode particles during these months. Elevated AE values are commonly associated with anthropogenic aerosols, biomass-burning emissions, and secondary aerosol formation processes, whereas lower values indicate a relatively greater contribution from coarse particles such as sea salt and mechanically generated aerosols [10,14]. The persistence of high AE values throughout the annual cycle suggests that fine particles constitute the dominant aerosol population over Penang regardless of season.

The Fine Mode Fraction exhibited relatively stable behavior compared with AOD, with monthly values generally ranging between approximately 0.65 and 0.80. The highest η values occurred during March and April, coinciding with elevated AE values and increased aerosol loading. This agreement between AE and η indicates enhanced fine-particle dominance during the first inter-monsoon period. Conversely, lower η values were observed during November and December, suggesting a modest increase in coarse-particle influence, likely associated with marine aerosols transported from surrounding oceanic regions.

A notable feature of Figure 1 is the simultaneous enhancement of AOD, AE, and η during several months, particularly March, April, and September. Such behavior indicates that increases in aerosol loading are primarily associated with fine-mode aerosol accumulation rather than increases in coarse particles. This pattern is characteristic of urban and coastal environments in Southeast Asia where anthropogenic emissions, secondary aerosol formation, and biomass-burning aerosols frequently dominate atmospheric aerosol populations [6,11].

Overall, the monthly climatology demonstrates that aerosol size characteristics over Penang are strongly influenced by fine-mode particles throughout the year. Although aerosol loading varies considerably between months, the consistently high AE and η values indicate a persistent fine-particle-dominated aerosol regime. These findings highlight the importance of anthropogenic and combustion-related aerosols in shaping the aerosol environment of this tropical coastal region.

C. Interannual Variability of Aerosol Size Characteristics.

Figure 2 presents the annual distribution of Ångström Exponent (AE) over Penang during the 2018–2022 study period. The AE distributions remained consistently above 1.0 in all years, indicating the persistent dominance of fine-mode aerosols throughout the observation period. The relatively stable median values, generally ranging between approximately 1.2 and 1.3, suggest that the overall aerosol size characteristics of the region did not undergo substantial long-term changes despite fluctuations in aerosol loading and atmospheric conditions.

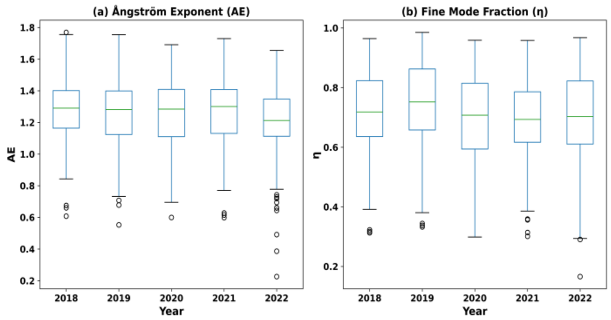

Figure 2. Annual distributions of (a) Ångström Exponent (AE) and (b) Fine Mode Fraction (η) over Penang, Malaysia.

The AE distributions (Figure 2a) were consistently centered above 1.2 in all years, with median values ranging from approximately 1.21 to 1.30. The interquartile ranges were also similar among years, suggesting limited long-term changes in aerosol particle size characteristics. The persistence of AE values above 1.0 indicates that fine particles remained the dominant component of the atmospheric aerosol population throughout the study period. Although several low-value outliers were observed, particularly in 2022, these events represented only a small fraction of total observations and likely corresponded to episodic increases in coarse-particle influence associated with marine aerosol transport or local resuspension processes [18].

The annual FMF distributions (Figure 2b) further support the predominance of fine-mode aerosols over Penang. Median η values remained close to 0.70–0.75 throughout the study period, indicating that approximately 70–75% of total aerosol optical depth was contributed by fine particles. Among all years, 2019 exhibited the highest median FMF and the widest upper distribution, suggesting enhanced fine-particle dominance during that year. In contrast, 2021 and 2022 showed slightly lower median FMF values and a greater occurrence of low-value outliers, reflecting occasional periods of increased coarse-particle contribution.

The consistency between AE and FMF distributions demonstrates strong agreement between the two independent aerosol size indicators. Years characterized by elevated AE values generally exhibited correspondingly high FMF values, indicating that increases in fine-particle abundance were reflected in both parameters. This agreement strengthens the interpretation that the aerosol environment over Penang is persistently influenced by anthropogenic emissions, secondary aerosol formation, and regional biomass-burning aerosols rather than coarse natural particles [15].

A notable feature of Figure 2 is the relatively narrow interannual variability compared with the broader short-term variability observed in monthly analyses. This suggests that seasonal and episodic fluctuations occur within a generally stable aerosol regime dominated by fine particles. Similar long-term persistence of fine-mode aerosol dominance has been reported in other urban and coastal environments across Southeast Asia, where anthropogenic activities and regional transport processes continuously contribute substantial quantities of submicron aerosol particles [19].

Overall, the interannual distributions of AE and FMF reveal a remarkably stable aerosol size structure over Penang during 2018–2022. The consistently high AE and FMF values indicate that fine-mode aerosols remained the dominant contributor to atmospheric aerosol loading throughout the study period, providing further evidence that combustion-related and anthropogenic sources play a major role in shaping regional aerosol characteristics.

D. Aerosol Regime Classification.

Table 2 presents the frequency distribution of aerosol regimes identified using the combined Fine Mode Fraction (η) and Ångström Exponent (AE) classification scheme. The results reveal that mixed aerosols constituted the most frequently observed aerosol regime over Penang, accounting for 47.89% of all observations. Fine-mode-dominated aerosols represented 45.05% of the dataset, while coarse-mode-dominated aerosols accounted for only 7.05%. These findings indicate that although fine particles strongly influence the aerosol environment, the atmosphere over Penang is characterized by substantial variability resulting from interactions among anthropogenic, marine, and regionally transported aerosol sources.

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Table 2. Frequency distribution of aerosol regimes over Penang, Malaysia during 2018–2022 based on combined Fine Mode Fraction (η) and Ångström Exponent (AE) classification criteria

Regime	Frequency (%)
Mixed Aerosols	47.89
Fine-mode Dominated	45.05
Coarse-mode Dominated	7.05

The high occurrence of mixed aerosols suggests that multiple aerosol sources frequently contribute simultaneously to the atmospheric column. As a coastal urban environment, Penang is exposed to emissions from transportation, industrial activities, biomass-burning plumes, and marine aerosol production. The coexistence of these aerosol types promotes transitional aerosol conditions in which neither fine nor coarse particles completely dominate the aerosol population. Similar mixed-aerosol regimes have been reported across Southeast Asia, where complex meteorological conditions and diverse emission sources create highly heterogeneous aerosol environments [20].

Fine-mode-dominated aerosols accounted for nearly half of all observations, highlighting the strong influence of anthropogenic and combustion-related emissions within the study region. The substantial contribution of fine particles is consistent with the elevated FMF and AE values reported in previous sections and reflects the importance of urban activities, secondary aerosol formation, and regional biomass-burning transport. During periods of enhanced biomass-burning activity, fine particles can remain suspended in the atmosphere for extended periods and be transported over large distances, significantly increasing their contribution to total aerosol loading [21].

In contrast, coarse-mode-dominated aerosols occurred relatively infrequently, representing only 7.05% of observations. The limited occurrence of this regime indicates that large particles such as sea salt and mechanically generated dust generally played a secondary role in determining the aerosol optical characteristics of Penang. Nevertheless, the presence of coarse-mode events demonstrates the occasional influence of marine aerosol transport and natural aerosol sources, particularly during periods characterized by stronger wind speeds and enhanced ocean-atmosphere interactions [19].

The near-equal occurrence of mixed aerosols and fine-mode-dominated aerosols provides important insight into the aerosol environment of Penang. While anthropogenic emissions constitute a major aerosol source, the region cannot be considered exclusively fine-particle dominated because interactions with marine and transported aerosols frequently modify atmospheric aerosol properties. This balance between anthropogenic and natural influences is characteristic of tropical coastal regions located within the Maritime Continent, where local emissions are continuously modulated by regional atmospheric circulation patterns [22].

Overall, the aerosol regime classification demonstrates that Penang experiences a predominantly fine-particle-influenced atmosphere with substantial contributions from mixed aerosol conditions and only limited occurrences of coarse-particle dominance. These findings reinforce the importance of considering both local emissions and regional transport processes when evaluating aerosol variability in tropical coastal environments.

E. Relationship Between Ångström Exponent and Fine Mode Fraction.

Figure 3 illustrates the relationship between Ångström Exponent (AE) and Fine Mode Fraction (η) derived from AERONET SDA observations over Penang during the period 2018–2022. Both parameters are widely used indicators of aerosol size characteristics and are expected to exhibit a positive relationship because they independently respond to changes in the relative abundance of fine and coarse aerosol particles.

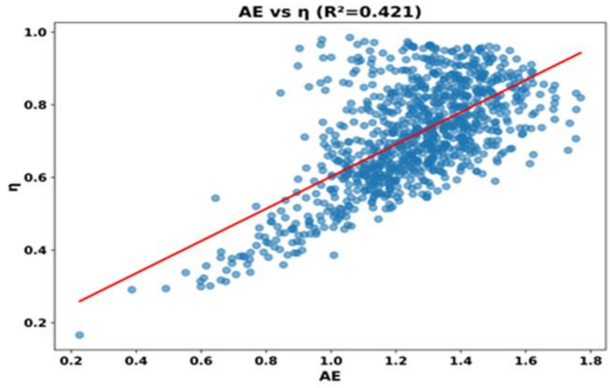

Figure 3. Relationship between Ångström Exponent (AE) and Fine Mode Fraction (η) over Penang, Malaysia during 2018–2022. The red line represents the linear regression fit, while the coefficient of determination (R^2 = 0.421) indicates the proportion of FMF variability explained by changes in AE.

The scatter distribution reveals a clear positive association between AE and η, indicating that increases in the relative contribution of fine particles are generally accompanied by higher Ångström Exponent values. The fitted regression line further demonstrates this positive trend, while the coefficient of determination (R^2 = 0.421) indicates that approximately 42.1% of the variability in Fine Mode Fraction can be explained by variations in AE. This relationship confirms that both parameters provide consistent information regarding aerosol size distributions and particle dominance within the atmospheric column.

Higher AE values, typically exceeding 1.3, were generally associated with FMF values greater than 0.70, indicating strong fine-particle dominance. These observations are characteristic of aerosol populations influenced by urban emissions, secondary aerosol formation, and biomass-burning particles. Conversely, lower AE values corresponded to reduced FMF values, reflecting increasing contributions from coarse particles such as sea salt and mechanically generated aerosols. Similar relationships between AE and FMF have been reported in numerous AERONET studies and are considered a fundamental characteristic of aerosol size distributions [23].

Although the overall relationship is positive, substantial scatter remains around the regression line, indicating that factors other than particle size also influence aerosol optical behavior. Variations in aerosol composition, particle mixing state, hygroscopic growth, and atmospheric humidity can modify optical properties and contribute to differences in FMF for similar AE values. Consequently, AE and FMF should be interpreted as complementary rather than interchangeable aerosol indicators [24].

The broad cluster of observations centered between AE values of approximately 1.1–1.5 and FMF values of 0.6–0.9 indicates that most aerosol conditions over Penang were dominated by fine particles. The relative scarcity of observations in the lower-left portion of the figure further supports the conclusion that coarse-particle-dominated conditions occurred infrequently throughout the study period. This finding agrees closely with the aerosol regime classification results presented in Section 3.4, where coarse-mode aerosols accounted for only a small fraction of total observations.

The moderate-to-strong relationship observed between AE and FMF provides additional evidence that aerosol size distributions over Penang are largely controlled by fine-mode particles originating from anthropogenic and combustion-related sources. The consistency among AE, FMF, and aerosol regime classifications strengthens confidence in the interpretation that fine aerosols constitute the dominant aerosol component within this tropical coastal environment. Similar AE–FMF relationships have been reported for urban and maritime locations worldwide and are frequently used to identify aerosol source characteristics and atmospheric aerosol regimes [25].

Overall, Figure 3 demonstrates that Ångström Exponent and Fine Mode Fraction are strongly linked indicators of aerosol size variability over Penang. The observed relationship confirms the predominance of fine-mode aerosols throughout the study period and highlights the usefulness of combining both parameters for aerosol regime characterization.

F. Seasonal Variability of Aerosol Regimes

Figure 4 illustrates the seasonal distribution of aerosol regimes over Penang using the combined Ångström Exponent (AE) and Fine Mode Fraction (η) framework. The clustering of observations within the upper-right portion of the diagram indicates that fine-mode aerosols dominated throughout most seasons, although noticeable seasonal differences in aerosol characteristics are evident. The figure further demonstrates that aerosol size distributions over Penang are strongly influenced by monsoonal circulation patterns and associated changes in atmospheric transport pathways.

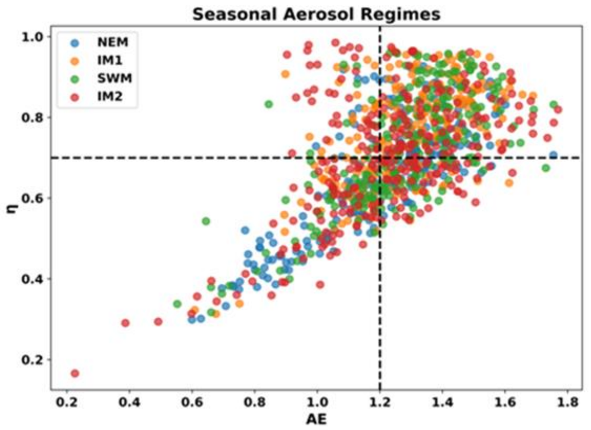

Figure 4. Seasonal distribution of aerosol regimes over Penang, Malaysia based on the relationship between Ångström Exponent (AE) and Fine Mode Fraction (η) during the Northeast Monsoon (NEM), First Inter-Monsoon (IM1), Southwest Monsoon (SWM), and Second Inter-Monsoon (IM2) periods

The Northeast Monsoon (NEM) exhibited a relatively broad distribution of observations, with several points extending toward lower AE and η values. This pattern suggests occasional enhancement of coarse-particle contributions, likely associated with increased marine aerosol influence originating from surrounding oceanic regions. The stronger winds and enhanced moisture transport characteristic of the Northeast Monsoon can increase sea-salt aerosol production, resulting in reduced fine-particle dominance compared with other seasons [19].

The First Inter-Monsoon period (IM1) displayed one of the strongest concentrations of observations within the fine-mode-dominated region of the diagram. Most observations were characterized by AE values exceeding 1.2 and η values above 0.70, indicating enhanced contributions from fine particles. The relatively stagnant atmospheric conditions and reduced rainfall frequently observed during inter-monsoon periods can promote aerosol accumulation and secondary particle formation, leading to increased fine-mode aerosol dominance [16].

The Southwest Monsoon (SWM) also exhibited a strong clustering within the fine-mode-dominated sector. This behavior is consistent with the influence of regional biomass-burning emissions transported from neighboring parts of Southeast Asia during the dry season. Long-range transport of smoke aerosols during the Southwest Monsoon has been widely recognized as a major contributor to elevated aerosol loading across the Maritime Continent [21,22]. The prevalence of observations with high AE and η values during this season suggests that transported combustion aerosols significantly influence aerosol size characteristics over Penang.

The Second Inter-Monsoon period (IM2) demonstrated the greatest dispersion among all seasons, with observations distributed across both mixed and fine-mode-dominated regimes. Several high η observations approaching 1.0 were

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recorded during this period, indicating episodes of exceptionally strong fine-particle dominance. At the same time, the presence of lower AE and η observations suggests occasional contributions from coarse particles and mixed aerosol populations. This variability likely reflects the transitional nature of the inter-monsoon season, during which atmospheric circulation patterns are less stable and multiple aerosol sources can influence the region simultaneously [20].

Overall, Figure 4 confirms that fine-mode aerosols dominate aerosol conditions in all seasons, but their relative importance varies according to monsoonal conditions. The First Inter-Monsoon and Southwest Monsoon periods exhibit the strongest fine-particle influence, whereas the Northeast Monsoon shows greater evidence of marine aerosol contributions. These seasonal differences highlight the combined effects of local emissions, regional biomass-burning transport, and monsoonal circulation in shaping aerosol size distributions over Penang. The consistency between seasonal regime distributions, annual AE–FMF relationships, and aerosol regime frequencies further reinforces the conclusion that fine particles constitute the principal component of atmospheric aerosols within this tropical coastal environment.

CONCLUSION

This study examined aerosol size characteristics over Penang, Malaysia, using AERONET Version 3 SDA observations from 2018 to 2022. The results revealed that the aerosol environment was consistently dominated by fine-mode particles, as evidenced by the high mean Fine Mode Fraction (0.713) and Ångström Exponent (1.251). Monthly and interannual analyses showed relatively stable aerosol size distributions despite variations in aerosol loading, indicating persistent influence from anthropogenic emissions, secondary aerosol formation, and regional biomass-burning activities. Aerosol regime classification demonstrated that mixed aerosols and fine-mode-dominated aerosols together accounted for more than 90% of all observations, while coarse-mode aerosols occurred infrequently. The positive relationship between AE and FMF further confirmed the dominant role of fine particles in controlling aerosol optical properties over the study area. Seasonal analyses highlighted the influence of monsoonal circulation, with enhanced fine-particle dominance during the inter-monsoon and Southwest Monsoon periods and increased marine aerosol influence during the Northeast Monsoon. Overall, the study demonstrates that Penang exhibits a predominantly fine-particle aerosol regime characteristic of tropical coastal urban environments. These findings contribute to a better understanding of aerosol size variability in Southeast Asia and provide a useful baseline for future investigations of aerosol–climate interactions, transboundary haze events, and regional air-quality management.

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