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Long-Term Variability and Partitioning of Fine- and Coarse-Mode Aerosols over Penang, Malaysia: Insights from AERONET SDA Observations.

By

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Abstract

Atmospheric aerosols influence air quality, visibility, and climate through their interactions with solar radiation and atmospheric processes. This study quantified the contributions of fine- and coarse-mode aerosols over Penang, Malaysia, using AERONET Version 3 Spectral Deconvolution Algorithm (SDA) Level 2.0 observations from 2018 to 2022. Daily measurements of total aerosol optical depth (τ_a), fine-mode aerosol optical depth (τ_f), and coarse-mode aerosol optical depth (τ_c) at 500 nm were analyzed to investigate monthly, seasonal, and interannual aerosol variability. The mean values of τa, τ_f, and τc were 0.284 ± 0.210, 0.215 ± 0.202, and 0.069 ± 0.045, respectively, indicating moderate aerosol loading with a strong dominance of fine-mode particles. Fine-mode aerosols contributed an average of 71.31% of total aerosol loading, whereas coarse-mode aerosols accounted for 28.69%. Aerosol loading peaked during September and reached its highest annual mean value in 2019. Seasonal analysis revealed the greatest aerosol loading and strongest fine-mode dominance during the First Inter-monsoon period, while the Northeast Monsoon exhibited the lowest aerosol loading and highest coarse-mode contribution. Pearson correlation analysis showed a weak positive relationship between τf and τc ($r = 0.074$, $p < 0.05$), suggesting that the two aerosol modes are influenced by different source mechanisms and atmospheric processes. Overall, the results indicate that aerosol variability over Penang is controlled primarily by fine-mode aerosols associated with anthropogenic emissions and regional transport, while coarse-mode aerosols provide a relatively stable marine background component.

Keywords- *AERONET, Aerosol Optical Depth, Fine-Mode Aerosols Coarse-Mode Aerosols; Penang.*

Introduction

Atmospheric aerosols play a critical role in the Earth's climate system through their interactions with solar radiation, clouds, and atmospheric chemistry. Aerosol particles can directly influence the radiative balance of the atmosphere by scattering and absorbing incoming solar radiation and indirectly modify cloud properties by acting as cloud condensation nuclei, thereby affecting climate variability at regional and global scales [1,2]. In addition to their climatic effects, aerosols contribute significantly to air quality degradation, visibility reduction, and adverse human health impacts, particularly in rapidly urbanizing regions [3].

Aerosol Optical Depth (AOD) is one of the most widely used parameters for characterizing the atmospheric aerosol burden. However, total AOD alone does not provide sufficient information regarding aerosol size distribution, which strongly influences aerosol transport, residence time, and radiative properties [4]. Aerosols are generally classified into fine-mode and coarse-mode particles. Fine-mode aerosols are typically associated with anthropogenic activities, biomass burning, industrial emissions, and secondary aerosol formation, whereas coarse-mode aerosols are primarily generated from natural sources such as mineral dust and marine sea salt aerosols [5].

The distinction between fine- and coarse-mode aerosols is particularly important in tropical coastal environments where multiple aerosol sources coexist. Coastal urban regions are influenced simultaneously by marine aerosols, urban-industrial emissions, vehicular activities, and long-range transported particles. Consequently, the relative contributions of fine- and coarse-mode aerosols may exhibit substantial seasonal and interannual variability [6]. Quantifying the partitioning of total aerosol loading into fine and coarse components is therefore essential for understanding dominant aerosol sources and their environmental implications.

Ground-based observations from the Aerosol Robotic Network (AERONET) provide one of the most reliable datasets for aerosol characterization worldwide. The global AERONET network supplies long-term, quality-assured measurements of aerosol optical properties using standardized sun-photometer observations [7]. Recent improvements in the AERONET Version 3 processing algorithms have enhanced data quality through improved calibration procedures, cloud screening methods, and quality assurance protocols [8]. Furthermore, the Spectral Deconvolution Algorithm (SDA) developed for AERONET retrievals enables the separation of total aerosol optical depth into fine-mode aerosol optical depth (τf) and coarse-mode aerosol optical depth (τc), providing valuable information on aerosol size characteristics and source contributions [9].

Penang, Malaysia, is a rapidly developing tropical coastal region located in the northern part of Peninsular Malaysia. The region experiences complex aerosol conditions arising from the combined influence of urban emissions, industrial activities, marine aerosols, and episodic transboundary haze events originating from biomass-burning activities across Southeast Asia [10]. While previous studies have investigated aerosol optical properties, monsoonal variability, and aerosol radiative effects over Penang and other parts of Malaysia, limited attention has been given to the long-term partitioning of aerosol loading into fine- and coarse-mode fractions using AERONET SDA retrievals [10,11].

Therefore, this study aims to quantify the relative contributions of fine- and coarse-mode aerosols over Penang, Malaysia, using AERONET Version 3 SDA Level 2.0 observations from 2018 to 2022. Specifically, the study investigates the temporal variability of total, fine-mode, and coarse-mode aerosol optical depths, evaluates seasonal variations in aerosol partitioning under different monsoonal regimes, and assesses the relative dominance of fine and coarse aerosol fractions. The findings provide new insights into aerosol size characteristics and dominant aerosol regimes in a tropical coastal environment and contribute to a better understanding of aerosol variability in Southeast Asia.

MATERIALS AND METHODS

A. Study Area

The study utilized aerosol observations obtained from the USM Penang AERONET station located at Universiti Sains Malaysia (USM), Penang, Malaysia (5.3584°N, 100.3023°E; 51 m above sea level). Penang is situated along the northwestern coast of Peninsular Malaysia and experiences a tropical maritime climate characterized by persistently high temperatures, elevated humidity, and substantial rainfall throughout the year. The region is influenced by the Northeast Monsoon, Southwest Monsoon, and two inter-monsoon periods, which significantly affect regional atmospheric circulation and aerosol transport patterns.

Penang represents a complex tropical coastal environment where aerosols originate from multiple natural and anthropogenic sources. Major aerosol contributors include urban and industrial emissions, vehicular activities, marine aerosols from the Strait of Malacca, and transboundary haze transported from biomass-burning regions across Southeast Asia. The coexistence of these aerosol sources makes Penang an ideal location for investigating aerosol size characteristics and the relative contributions of fine- and coarse-mode particles.

B. AERONET SDA Dataset

The aerosol dataset used in this study was obtained from the Aerosol Robotic Network (AERONET), a globally distributed network of ground-based CIMEL sun-photometers designed to provide standardized and quality-assured measurements of aerosol optical properties [7]. The present analysis employed Version 3 Spectral Deconvolution Algorithm (SDA) Level 2.0 retrieval products, which incorporate improved calibration procedures, cloud-screening algorithms, and quality assurance protocols relative to earlier data versions [8].

The SDA retrieval algorithm separates total aerosol optical depth into fine-mode and coarse-mode components using the spectral dependence of aerosol extinction [9]. Daily averaged Level 2.0 observations from the USM Penang station covering the period January 2018 to December 2022 were analyzed. Following quality assurance procedures implemented within the AERONET processing system, a total of 950 daily observations were available for subsequent analysis.

The principal aerosol parameters investigated in this study were total aerosol optical depth at 500 nm (τa), fine-mode aerosol optical depth at 500 nm (τf), and coarse-mode aerosol optical depth at 500 nm (τc). The relationship among these parameters is expressed as:

$$,\tau_a = \tau_f + \tau_c \quad (1)$$

where τ_a represents the total aerosol optical depth, τ_f denotes the fine-mode aerosol optical depth, and τ_c denotes the coarse-mode aerosol optical depth.

To quantify the relative contribution of fine-mode and coarse-mode aerosols to the total aerosol burden, the fine-mode contribution (FC) and coarse-mode contribution (CC) were calculated as percentages of the total aerosol optical depth.

The fine-mode contribution was computed as:

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

Similarly, the coarse-mode contribution was determined as:

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

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:

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

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

All statistical analyses, data processing procedures, and graphical visualizations were performed using Python 3.13 with the Pandas, NumPy, Matplotlib, and SciPy scientific computing libraries.

RESULT AND DISCUSSION

A. Statistics of Aerosol Components

Table 1 presents the descriptive statistics of total aerosol optical depth (τ_a), fine-mode aerosol optical depth (τ_f), coarse-mode aerosol optical depth (τc), and their corresponding percentage contributions over Penang, Malaysia, during the period 2018–2022.

Table 1. Descriptive statistics of total aerosol optical depth (τ_a), fine-mode aerosol optical depth (τ_f), coarse-mode aerosol optical depth (τ_c), fine-mode contribution (FC), and coarse-mode contribution (CC).

Aerosols	Mean	SD	Minimum	Maximum
tau_a	0.284	0.21	0.041	2.615
tau_f	0.215	0.202	0.024	2.576
tau_c	0.069	0.045	0.011	0.603
Fine_%	71.311	14.685	16.305	98.526
Coarse_%	28.689	14.685	1.474	83.695

The mean total aerosol optical depth (τ_a) was 0.284 ± 0.210, indicating a moderate aerosol loading over the study area. The observed values ranged from 0.041 to 2.615, reflecting substantial temporal variability in atmospheric aerosol conditions. The relatively large standard deviation compared with the mean suggests the occurrence of episodic aerosol enhancement events, likely associated with regional haze episodes, enhanced anthropogenic emissions, and variations in atmospheric transport processes. Similar levels of aerosol loading have been reported for several urban and coastal locations in Southeast Asia, where both local emissions and transboundary aerosol transport contribute significantly to atmospheric aerosol concentrations [10].

The fine-mode aerosol optical depth (τf) exhibited a mean value of 0.215 ± 0.202, accounting for the largest proportion of the total aerosol burden. Fine-mode AOD values varied between 0.024 and 2.576, demonstrating considerable fluctuations throughout the study period. The substantial contribution of fine particles indicates the strong influence of anthropogenic and combustion-related aerosol sources, including urban emissions, industrial activities, vehicular exhaust, and secondary aerosol formation processes. Fine-mode aerosols are generally characterized by longer atmospheric residence times and greater transport potential than coarse particles, making them dominant contributors to aerosol loading in many urban and coastal environments [4,6].

In contrast, the coarse-mode aerosol optical depth (τ_c) exhibited a considerably lower mean value of 0.069 ± 0.045. The coarse-mode component ranged from 0.011 to 0.603, indicating that coarse particles constituted a smaller but persistent fraction of the atmospheric aerosol population. The presence of coarse aerosols is likely associated with marine sea-salt particles originating from the nearby Strait of Malacca, together with occasional contributions from mechanically generated particles and long-range transported dust aerosols. The lower variability observed for τc compared with τf suggests that coarse-mode aerosols were influenced primarily by relatively stable natural sources.

Analysis of aerosol partitioning further revealed a clear dominance of fine-mode aerosols over Penang throughout the study period. The average fine-mode contribution (FC) was 71.31 ± 14.69%, while the average coarse-mode contribution (CC) was 28.69 ± 14.69%. Fine-mode contributions reached a maximum of 98.53%, whereas coarse-mode contributions attained a maximum of 83.70% during specific events. These results indicate that the atmospheric aerosol environment over Penang was predominantly controlled by fine particles, although coarse-mode aerosols occasionally became important under particular meteorological conditions.

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The predominance of fine-mode aerosols observed in this study is consistent with previous investigations conducted across Southeast Asia, where anthropogenic emissions and biomass-burning aerosols frequently dominate columnar aerosol loading [6]. The high mean fine-mode contribution exceeding 70% suggests that regional and local combustion-related sources play a major role in determining aerosol characteristics over Penang. Consequently, changes in anthropogenic emissions and regional atmospheric transport are likely to exert a stronger influence on aerosol variability than natural coarse-particle sources during most periods of the year.

Overall, the descriptive statistics demonstrate that aerosol loading over Penang during 2018–2022 was characterized by substantial temporal variability and a pronounced dominance of fine-mode particles. These findings provide an important foundation for understanding the monthly, seasonal, and interannual aerosol variations discussed in the subsequent sections.

B. Monthly Variability of Aerosols type

Figure 1 illustrates the monthly climatological variability of total aerosol optical depth (τ_a), fine-mode aerosol optical depth (τ_f), and coarse-mode aerosol optical depth (τ_c) over Penang during the period 2018–2022. Distinct seasonal fluctuations were observed for all aerosol components, indicating the influence of regional meteorological conditions and varying aerosol source strengths throughout the year.

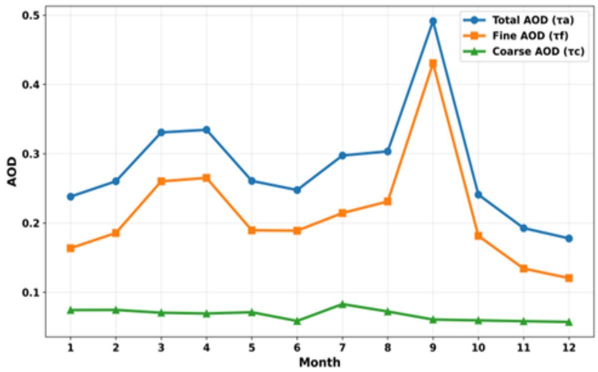

Figure 1. Monthly climatological variations of total aerosol optical depth

The total aerosol optical depth exhibited considerable month-to-month variability, with values ranging from approximately 0.18 to 0.49. Elevated aerosol loading was observed during March and April, when τ_a exceeded 0.33, suggesting enhanced aerosol accumulation during the First Inter-monsoon period. Following a moderate decline during May and June, aerosol loading increased again during July and August before reaching its annual maximum in September ($\tau_a \approx 0.49$). Thereafter, τ_a decreased substantially from October onward, reaching the lowest values during November and December.

The seasonal pattern of fine-mode aerosol optical depth closely followed that of total aerosol optical depth, indicating that fine particles were the dominant contributor to aerosol variability throughout the study period. Fine-mode AOD increased from approximately 0.16 in January to about 0.26 during March and April, followed by a secondary increase during July and August. The highest fine-mode aerosol loading occurred in September ($\tau_f \approx 0.43$), coinciding with the maximum observed total aerosol optical depth. This behavior suggests that fluctuations in total aerosol loading were primarily controlled by changes in fine-mode aerosol abundance.

The pronounced September peak is likely associated with enhanced regional biomass-burning activity and transboundary aerosol transport occurring during the latter part of the Southwest Monsoon season. Similar increases in fine-mode aerosol loading during late boreal summer and early autumn have been reported across Southeast Asia and are commonly linked to biomass-burning emissions originating from Indonesia and surrounding regions [6,12]. Fine particles generated by combustion processes can remain suspended in the atmosphere for extended periods and may be transported over considerable distances, resulting in elevated columnar aerosol loading over downwind receptor regions.

In contrast, coarse-mode aerosol optical depth exhibited substantially lower values throughout the year, generally remaining between 0.06 and 0.08. The highest coarse-mode aerosol loading occurred in July ($\tau_c \approx 0.08$), while the lowest values were observed during September to December. Compared with fine-mode aerosols, the seasonal variability of τ_c was considerably weaker, indicating that coarse particles contributed a relatively stable background aerosol component. The persistence of coarse-mode aerosols throughout the year is likely associated with marine sea-salt particles generated over the nearby Strait of Malacca. Coastal regions are frequently characterized by continuous marine aerosol production, which tends to exhibit lower temporal variability than anthropogenic fine-mode aerosols [13].

A comparison of the three aerosol components clearly demonstrates the dominant influence of fine-mode aerosols on total aerosol loading over Penang. The temporal evolution of τ_a closely mirrors that of τ_f, whereas variations in τc are comparatively minor. This finding suggests that seasonal changes in aerosol concentrations are controlled primarily by fine particles originating from anthropogenic and combustion-related sources rather than by coarse-mode marine aerosols. The observed dominance of fine-mode aerosols is consistent with previous aerosol studies conducted in Southeast Asia, which have reported significant contributions from urban emissions, secondary aerosol formation, and regional biomass-burning activities [6,10].

Overall, the monthly climatological analysis indicates that aerosol variability over Penang is characterized by strong seasonal fluctuations dominated by fine-mode particles. The marked increase in aerosol loading during September highlights the importance of regional-scale aerosol transport processes, whereas the relatively stable coarse-mode component reflects the continuous influence of marine aerosols in this tropical coastal environment.

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C. Interannual Variability of Total, Fine- and Coarse-Mode Aerosols.

Figure 2 presents the interannual variability of total aerosol optical depth (τ_a), fine-mode aerosol optical depth (τ_f), and coarse-mode aerosol optical depth (τ_c) over Penang during the period 2018–2022. Considerable year-to-year variations were observed, indicating the influence of changing regional atmospheric conditions, emission patterns, and aerosol transport processes.

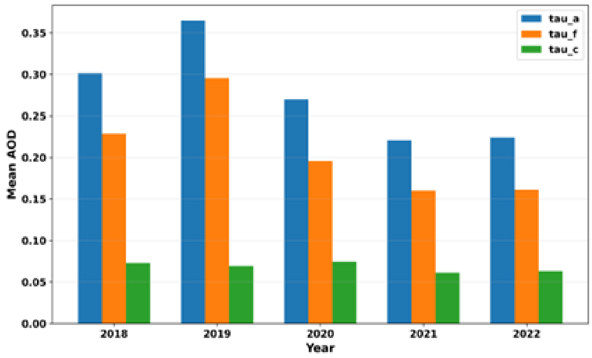

Figure 2. Interannual variations in mean total aerosol optical depth.

The highest annual mean total aerosol optical depth was recorded in 2019 (τ_a = 0.366), followed by 2018 (τ_a = 0.301) and 2020 (τ_a = 0.270). Subsequently, aerosol loading decreased markedly during 2021 (τ_a = 0.221) before showing a slight increase in 2022 (τ_a = 0.224). The elevated aerosol loading observed during 2019 suggests enhanced aerosol accumulation over Penang, while the substantial decline after 2020 indicates a reduction in atmospheric aerosol concentrations.

A similar temporal pattern was observed for fine-mode aerosol optical depth, which remained the dominant component of total aerosol loading throughout the study period. Fine-mode AOD increased from 0.228 in 2018 to 0.296 in 2019, representing the highest value recorded during the study period. Thereafter, τ_f decreased progressively to 0.196 in 2020 and approximately 0.160 in both 2021 and 2022. The close correspondence between τa and τ_f indicates that interannual variations in total aerosol loading were primarily controlled by changes in fine-mode aerosols. Such behavior is commonly observed in urban and industrialized regions where anthropogenic emissions and secondary aerosol formation dominate atmospheric aerosol composition [12,15].

In contrast, coarse-mode aerosol optical depth exhibited relatively limited interannual variability. Annual mean τc values remained within a narrow range of approximately 0.061–0.074 throughout the study period. The highest coarse-mode loading was observed in 2020 (τ_c = 0.074), while the lowest value occurred in 2021 (τ_c = 0.061). The relatively stable nature of τc suggests that coarse particles were influenced predominantly by persistent natural sources, particularly marine aerosols generated over the Strait of Malacca. Previous studies have shown that sea-salt aerosols often exhibit lower interannual variability than fine anthropogenic aerosols because their production is closely linked to regional meteorological conditions rather than emission intensity [13].

The pronounced reduction in both τ_a and τ_f during 2020–2021 may also reflect changes in anthropogenic activities associated with movement restrictions and reduced industrial and transportation emissions during the COVID-19 pandemic. Similar decreases in aerosol loading were reported across numerous regions worldwide, including Southeast Asia, where lockdown measures contributed to measurable reductions in atmospheric aerosol concentrations [16,17]. Although local emission reductions may have played a role, meteorological variability and fluctuations in regional aerosol transport likely also contributed to the observed changes.

Overall, the interannual analysis demonstrates that aerosol loading over Penang was characterized by a distinct peak in 2019 followed by a sustained decline during 2020–2022. The close agreement between the temporal evolution of τ_a and τ_f confirms the dominant influence of fine-mode aerosols on annual aerosol variability, whereas coarse-mode aerosols contributed a comparatively stable background component throughout the study period.

In addition to variations in aerosol loading, the relative contributions of fine-mode and coarse-mode aerosols exhibited notable consistency throughout the study period (Figure 3). Fine-mode aerosols remained the dominant component of the atmospheric aerosol column during all years, contributing approximately 70–75% of the total aerosol optical depth, whereas coarse-mode aerosols accounted for only 25–30%.

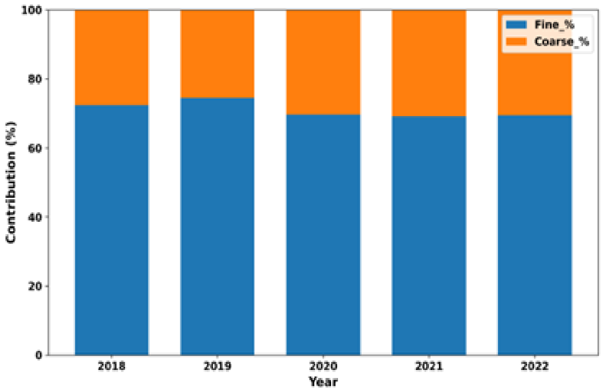

Figure 3. Annual percentage contributions of fine-mode aerosols (FC) and coarse-mode aerosols (CC) to total aerosol optical depth.

The highest fine-mode contribution was observed in 2019, when fine particles represented approximately 74.5% of the total aerosol burden. This coincided with the year of maximum aerosol loading identified in Figure 2, indicating that the enhanced aerosol concentrations during 2019 were primarily associated with increases in fine-mode particles rather than coarse aerosols. Since fine-mode aerosols are commonly linked to combustion-related emissions, industrial activities, urban pollution, and secondary aerosol formation processes, the elevated contribution observed during 2019 suggests a stronger influence of anthropogenic and regional

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combustion sources during that year [15,18].

Following 2019, the fine-mode contribution decreased slightly to approximately 70% during 2020 and remained relatively stable throughout 2021 and 2022. Despite the reduction in total aerosol optical depth after 2019, the proportional contribution of fine particles changed only marginally. This finding suggests that the processes controlling aerosol composition remained largely unchanged even as overall aerosol loading declined. In other words, reductions in aerosol concentration affected both aerosol modes simultaneously, while the fine-mode component continued to dominate the aerosol population.

Conversely, the coarse-mode contribution displayed only minor interannual fluctuations, ranging from approximately 25% to 31% during the study period. The highest coarse-mode contribution occurred in 2021, corresponding to the year with the lowest total aerosol optical depth. The relative increase in coarse-mode contribution during low-aerosol years does not necessarily indicate enhanced coarse-particle production; rather, it reflects the reduced dominance of fine-mode aerosols during periods of lower anthropogenic influence. Similar behavior has been reported in coastal environments where marine aerosols constitute a persistent background component while fine-mode aerosols exhibit greater temporal variability [13,19].

The relatively narrow range of annual fine-mode contributions observed throughout the study period demonstrates the stability of aerosol source characteristics over Penang. Even during years with substantial differences in total aerosol loading, the aerosol population remained overwhelmingly dominated by fine particles. Such behavior is typical of urbanized tropical environments influenced by persistent anthropogenic emissions and regional aerosol transport [14,18].

The results further indicate that interannual changes in aerosol loading were primarily associated with variations in fine-mode aerosol abundance rather than shifts in aerosol composition. Consequently, the observed aerosol variability over Penang appears to be driven mainly by fluctuations in anthropogenic and combustion-related aerosol sources, while marine coarse particles provide a comparatively stable background contribution. These findings reinforce the conclusion that fine-mode aerosols constitute the principal component of atmospheric aerosol loading over Penang and play the dominant role in controlling year-to-year aerosol variability.

D. Seasonal Aerosol Partitioning Characteristics.

Table 2 summarizes the seasonal variability of total aerosol optical depth (τ_a), fine-mode aerosol optical depth (τ_f), coarse-mode optical depth (τ_c), and their respective contributions to the atmospheric aerosol burden over Penang during 2018–2022. The results reveal pronounced seasonal differences in aerosol loading and aerosol partitioning, reflecting the influence of the regional monsoon system on aerosol production, transport, and removal processes.

Table 2. Seasonal mean values of total aerosol optical depth (τa), fine-mode aerosol optical depth (τ_f), coarse-mode aerosol optical depth (τ_c), fine-mode contribution (FC), and coarse-mode contribution (CC).

Season	tau_a	tau_f	tau_c	Fine_%	Coarse_%
NEM	0.228	0.159	0.07	66.421	33.579
IM1	0.332	0.262	0.07	76.764	23.236
SWM	0.284	0.212	0.072	72.091	27.909
IM2	0.289	0.226	0.063	70.18	29.82

The highest seasonal mean total aerosol optical depth was observed during the First Inter-monsoon (IM1), with τ_a reaching 0.332. This period was also characterized by the highest fine-mode aerosol optical depth (τ_f = 0.262) and the largest fine-mode contribution (FC = 76.76%). The enhanced fine-mode dominance during IM1 suggests increased accumulation of anthropogenic and secondary aerosols under relatively weak wind conditions and reduced atmospheric ventilation. Inter-monsoon periods in Malaysia are often associated with stagnant atmospheric conditions that favor aerosol accumulation and limit pollutant dispersion [20].

The Southwest Monsoon (SWM) recorded the second-highest aerosol loading (τa = 0.284), accompanied by a fine-mode contribution of 72.09%. Although total aerosol loading during SWM was lower than during IM1, the season exhibited the highest coarse-mode aerosol optical depth (τ_c = 0.072). The elevated coarse-mode component may be attributed to enhanced marine aerosol production associated with stronger regional winds over the Strait of Malacca, as well as contributions from long-range transported particles. At the same time, the relatively high fine-mode contribution indicates the continued influence of anthropogenic aerosols and regional biomass-burning emissions during this period [6,12].

The Second Inter-monsoon (IM2) exhibited a total aerosol optical depth of 0.289, with τf and τc values of 0.226 and 0.063, respectively. Fine-mode aerosols accounted for approximately 70.18% of the total aerosol burden, while coarse particles contributed 29.82%. The moderate aerosol loading observed during IM2 reflects the combined influence of local emissions, regional transport, and transitional meteorological conditions between the Southwest and Northeast Monsoon seasons.

The lowest aerosol loading was recorded during the Northeast Monsoon (NEM), when τa decreased to 0.228. This season also exhibited the lowest fine-mode aerosol optical depth (τf = 0.159) and the smallest fine-mode contribution (FC = 66.42%). Conversely, the coarse-mode contribution reached its maximum seasonal value of 33.58%. The reduction in fine-mode aerosols during NEM is likely associated with increased precipitation and more efficient wet removal processes, which are particularly effective in scavenging fine particles from the atmosphere [21]. The relative increase in coarse-mode contribution during this season reflects the reduced abundance of fine particles rather than a substantial enhancement of coarse aerosol production.

A comparison of the four seasons clearly demonstrates that fine-mode aerosols dominated the atmospheric aerosol burden throughout the year, with contributions consistently exceeding 66%. However, the degree of fine-mode dominance varied considerably across seasons. The strongest fine-mode influence occurred during IM1, whereas the weakest occurred during NEM. This seasonal pattern suggests that aerosol accumulation over Penang is strongly controlled by meteorological conditions governing atmospheric stability, precipitation, and regional transport pathways.

The observed seasonal variability is consistent with previous studies conducted across Malaysia and Southeast Asia, which have reported enhanced aerosol accumulation during inter-monsoon and southwest monsoon periods and lower aerosol loading during the wetter northeast monsoon season [10,20]. The results further demonstrate that although coarse-mode aerosols remain an important component of the atmospheric column, particularly in this coastal environment, fine-mode aerosols constitute the dominant fraction of aerosol loading throughout all monsoonal regimes.

Figure 4 provides a visual representation of the seasonal aerosol partitioning characteristics summarized in Table 2. The figure clearly demonstrates the persistent dominance of fine-mode aerosols throughout all monsoonal periods, with fine particles accounting for more than two-thirds of the total aerosol burden in every season.

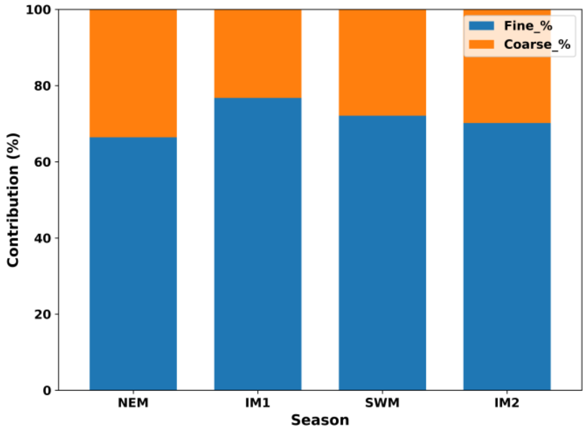

Figure 4. Seasonal contributions of fine-mode aerosols (FC) and coarse-mode aerosols (CC) to total aerosol optical depth

The most pronounced fine-mode dominance occurred during the First Inter-monsoon (IM1), when fine aerosols contributed approximately 76.8% of the total aerosol optical depth. This period was characterized by the highest total aerosol loading and the largest fine-mode aerosol optical depth, indicating favorable conditions for aerosol accumulation. The enhanced contribution of fine particles during IM1 suggests increased influence from anthropogenic emissions, secondary aerosol formation, and reduced atmospheric dispersion under relatively stagnant meteorological conditions.

During the Southwest Monsoon (SWM), fine-mode aerosols continued to dominate the atmospheric column, contributing approximately 72.1% of total aerosol loading. The elevated fine-mode fraction during this season may also reflect the influence of regional biomass-burning emissions and long-range transport processes that frequently affect the Maritime Continent during the dry season [12,22]. Previous studies have shown that transported smoke aerosols from biomass-burning regions are predominantly composed of fine particles, leading to enhanced fine-mode aerosol contributions across downwind receptor regions [6,22].

The Northeast Monsoon (NEM) exhibited the lowest fine-mode contribution (66.4%) and the highest coarse-mode contribution (33.6%). Although fine particles remained dominant, the relative increase in coarse-mode aerosols suggests a stronger influence of marine aerosols and enhanced removal of fine particles through precipitation scavenging. Increased rainfall associated with the Northeast Monsoon is known to reduce atmospheric fine-particle concentrations through efficient wet deposition processes [21].

The Second Inter-monsoon (IM2) displayed intermediate aerosol characteristics, with fine-mode aerosols contributing approximately 70.2% of total aerosol loading. The relatively small differences observed between SWM and IM2 indicate that aerosol source characteristics remained broadly similar during these periods, although changes in regional transport and local meteorological conditions likely influenced the observed variability.

Overall, Figure 4 confirms that aerosol partitioning over Penang is dominated by fine-mode particles throughout the year, while seasonal fluctuations primarily reflect changes in the relative importance of anthropogenic and natural aerosol sources. The persistence of fine-mode dominance across all seasons highlights the strong influence of urban emissions and regional transport processes on aerosol characteristics within this tropical coastal environment.

E. Relationship Between Fine- and Coarse-Mode Aerosols.

The relationship between fine-mode aerosol optical depth (τf) and coarse-mode aerosol optical depth (τc) was evaluated using Pearson's correlation analysis. The results yielded a correlation coefficient of $r = 0.074$ with a corresponding p-value of 0.0229, indicating a statistically significant but extremely weak positive relationship between the two aerosol components.

The low correlation coefficient suggests that variations in fine-mode and coarse-mode aerosols occurred largely independently throughout the study period. Although the positive sign of the correlation indicates that increases in one aerosol mode were occasionally accompanied by increases in the other, the magnitude of the relationship was too small to indicate a meaningful physical coupling between the two aerosol populations.

The weak association observed in this study is consistent with the fundamentally different origins of fine- and coarse-mode aerosols. Fine-mode particles are predominantly associated with anthropogenic emissions, biomass-burning activities, industrial processes, vehicular exhaust, and secondary aerosol formation, whereas coarse-mode particles are generally derived from marine aerosols, mechanically generated particles, and natural dust sources [5,13]. Similar weak relationships between fine- and coarse-mode aerosol fractions have been reported in coastal and maritime environments where multiple aerosol sources operate simultaneously and respond differently to meteorological forcing [23].

The results further indicate that fluctuations in total aerosol optical depth over Penang were primarily controlled by variations in fine-mode aerosols rather than coordinated changes in both aerosol modes. This finding is consistent with the interannual and seasonal analyses presented in previous sections, which demonstrated that fine particles accounted for approximately 66–77% of total aerosol loading across all monsoonal periods and years. Previous AERONET-based studies have likewise shown that temporal changes in aerosol optical depth over tropical urban environments are largely driven by fine-mode aerosols associated with anthropogenic and biomass-burning emissions [24].

Although the p-value indicates statistical significance, this result should be interpreted cautiously due to the relatively large sample size ($n = 950$). Statistical significance does not necessarily imply a strong physical relationship. In atmospheric datasets, weak correlations frequently become statistically significant when large numbers of observations are available. Therefore, the observed correlation is best interpreted as evidence that fine-mode and coarse-mode aerosols exhibit largely independent temporal behavior rather than a strong physical linkage.

The limited coupling between τf and τc also reflects the influence of distinct aerosol production and removal mechanisms. Fine particles are strongly affected by combustion emissions, secondary aerosol formation, and regional transport processes, whereas coarse particles are controlled primarily by sea-salt generation, mechanical processes, and local meteorological conditions. Similar conclusions have been reported from long-term aerosol observations across Southeast Asia, where aerosol variability was found to be governed primarily by changes in fine-mode particle abundance while coarse-mode aerosols remained comparatively stable [25].

Overall, the correlation analysis reinforces the conclusion that the aerosol environment over Penang is dominated by fine-mode particles and that the mechanisms controlling fine- and coarse-mode aerosol variability differ substantially. The independence of these aerosol modes highlights the importance of aerosol partitioning analyses for accurately characterizing aerosol sources and understanding atmospheric aerosol dynamics in tropical coastal environments.

CONCLUSION

This study examined the temporal variability and partitioning of aerosols over Penang, Malaysia, using AERONET SDA Level 2.0 observations from 2018 to 2022. The results showed that the aerosol environment was consistently dominated by fine-mode particles, which contributed approximately 71% of total aerosol loading compared with 29% from coarse-mode aerosols. Monthly analysis identified September as the period of maximum aerosol loading, while seasonal analysis revealed the highest aerosol concentrations during the First Inter-monsoon and the lowest during the Northeast Monsoon. Interannual variability indicated peak aerosol loading in 2019 followed by a decline during 2020–2022, although the dominance of fine-mode aerosols remained largely unchanged. The weak correlation between fine- and coarse-mode aerosol optical depths ($r = 0.074$) suggests that the two aerosol modes are controlled by distinct source mechanisms and atmospheric processes. Overall, the findings demonstrate that aerosol variability over Penang is governed primarily by fine-mode aerosols associated with anthropogenic activities and regional transport, whereas coarse-mode aerosols constitute a relatively stable marine background component. These results provide valuable insight into aerosol size characteristics in a tropical coastal environment and establish a baseline for future investigations of aerosol impacts on air quality, radiation, and climate across Southeast Asia...

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