Jurnal Reka Lingkungan
ISSN(p): 2337-6228 | ISSN(e): 2722-6077 | Vol. 14 | No. 1 | Hal. 13-26
DOI: http://dx.doi.org/10.26760/rekalingkungan.v14i1.13-26 April 2026

TRACING THE SOURCES AND TRANSPORT PATHWAYS OF PARTICULATE IN JAKARTA USING THE WRF-HYSPLIT MODEL DURING THE JULY 2023 POLLUTION EPISODE

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ABSTRACT

PM2.5 pollution remains a critical environmental and public health issue in Jakarta, particularly during the dry season when unfavorable meteorological conditions enhance pollutant accumulation. This study examines the sources and transport pathways of PM2.5 during a severe pollution episode in July 2023, utilizing a combined Weather Research and Forecasting (WRF) and Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) modeling approach. Meteorological simulations were evaluated against surface observations, while backward trajectory analyses were conducted using multiple meteorological datasets to assess the consistency of transport. The results indicate that PM2.5 transport into Jakarta was predominantly influenced by air masses originating from the east and southeast, associated with industrial activities, power plants, and local fire events in surrounding regions. The presence of the southeast monsoon contributed to reduced atmospheric dispersion, resulting in prolonged pollutant residence times over the urban area. Despite some limitations in wind speed simulation, the WRF model adequately represented key meteorological parameters relevant to trajectory analysis. These findings highlight that Jakarta's air pollution is driven by the combined effects of local emissions and regional transport processes, emphasizing the need for integrated air quality management strategies that extend beyond administrative boundaries.

***Keywords**: $PM_{2,5}$, Air Pollution, Hysplit, Jakarta, WRF Model*

ABSTRAK

Pencemaran PM2.5 masih menjadi persoalan lingkungan dan kesehatan masyarakat yang serius di Jakarta, terutama pada musim kemarau ketika kondisi meteorologi tidak mendukung dispersi polutan. Penelitian ini bertujuan mengkaji sumber dan jalur transport PM2.5 selama kejadian pencemaran tinggi pada Juli 2023 menggunakan pendekatan pemodelan Weather Research and Forecasting (WRF) dan Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT). Simulasi meteorologi diverifikasi menggunakan data observasi permukaan, sementara analisis lintasan balik dilakukan dengan memanfaatkan beberapa dataset meteorologi untuk menilai konsistensi pola transport polutan. Hasil penelitian menunjukkan bahwa transport PM2.5 menuju Jakarta didominasi oleh massa udara yang berasal dari arah timur dan tenggara, yang berkaitan dengan aktivitas industri, pembangkit listrik, serta kejadian kebakaran lokal di wilayah sekitarnya. Keberadaan monsun tenggara berperan dalam menghambat dispersi atmosfer, sehingga meningkatkan waktu tinggal polutan di atas kawasan perkotaan. Meskipun simulasi kecepatan angin menunjukkan keterbatasan, model WRF mampu merepresentasikan parameter meteorologi utama yang relevan untuk analisis trajektori. Hasil ini menegaskan bahwa pencemaran udara di Jakarta dipengaruhi oleh kombinasi emisi lokal dan transport regional, sehingga upaya pengendalian kualitas udara memerlukan strategi pengelolaan terpadu yang melampaui batas administratif wilayah.

***Kata kunci**: $PM_{2,5}$, Pencemaran udara, Hysplit, Jakarta, model WRF*

1. INTRODUCTION

Fine particulate matter with an aerodynamic diameter of less than 2.5 μm (PM2.5) is widely recognized as one of the most hazardous air pollutants due to its ability to penetrate deep into the respiratory system and enter the bloodstream, leading to severe adverse health effects. Numerous studies have linked long-term exposure to PM2.5 with increased risks of cardiovascular diseases, respiratory disorders, and neurological impairments, including dementia (Hayes et al., 2020; Kawi et al., 2023). Owing to these impacts, the World Health Organization (WHO) has established stringent air quality guidelines for PM2.5, recommending a 24-hour mean concentration of 15 μg/m³ and an annual mean of 5 μg/m³ (WHO, 2006). Beyond health concerns, PM2.5 also affects environmental quality by reducing visibility, contributing to haze formation, altering radiative balance, and impacting terrestrial and aquatic ecosystems through deposition processes (McNeill, 2017).

Jakarta, the capital city of Indonesia, represents one of the most critical urban environments in Southeast Asia with respect to air pollution. Characterized by rapid urbanization, high population density, heavy vehicular traffic, and extensive industrial activities, Jakarta is particularly vulnerable to elevated PM2.5 concentrations (BPS, 2023). During the dry season, air quality conditions often deteriorate significantly, driven by reduced precipitation, stable atmospheric conditions, and prevailing monsoonal wind patterns. In July 2023, Jakarta experienced an extreme PM2.5 pollution episode, with concentrations reaching 139 μg/m³, approximately 27.8 times higher than the WHO daily guideline, highlighting the severity of the air quality crisis and its potential implications for public health and environmental sustainability (AirNow, 2023).

Understanding the sources and transport mechanisms of PM2.5 is crucial for effective air quality management in megacities like Jakarta. PM2.5 originates from a variety of anthropogenic activities, including fossil fuel combustion, industrial emissions, vehicular exhaust, and biomass burning (Mustafa et al., 2023). Due to its small size and long atmospheric residence time, PM2.5 can be transported over regional to long-range distances, allowing emissions from surrounding regions to contribute significantly to urban pollution levels (McNeill, 2017). In Jakarta, meteorological factors such as wind speed, wind direction, rainfall, and seasonal monsoon circulation play a critical role in governing pollutant dispersion, accumulation, and removal (Enhakhoirunnisa et al., 2023).

Previous studies have applied trajectory-based models, particularly the Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model, to investigate aerosol transport and source regions in various Indonesian cities. Research in Bandung and Sorong, for example, has demonstrated that PM2.5 pollution can be strongly influenced by regional transport associated with prevailing wind patterns and maritime air masses (Melinda & Nuryanto, 2023; Nurlatifah & Driejana, 2019). These studies highlight the significant role of atmospheric circulation in influencing urban air quality. However, studies specifically addressing Jakarta's PM2.5 sources and transport pathways remain limited, particularly those that explicitly focus on extreme pollution episodes and systematically evaluate the influence of different meteorological inputs on trajectory outcomes.

Most existing studies on PM2.5 in Jakarta have primarily emphasized concentration analysis, emission inventories, or model simulations using single meteorological datasets. As a result, uncertainties persist regarding how variations in meteorological resolution and data sources impact the identification of dominant transport pathways and source regions, particularly during severe pollution events. Furthermore, the role of the southeast monsoon in enhancing pollutant persistence and long-range transport during the dry season has not been comprehensively examined using a comparative, multi-dataset modeling framework (Kusumaningtyas et al., 2018; Lestari et al., 2021).

To address these gaps, this study investigates the sources and transport pathways of PM2.5 in Jakarta during the extreme pollution episode in July 2023, utilizing an integrated Weather Research and Forecasting (WRF)-HYSPLIT modeling approach. High-resolution WRF simulations are validated against surface meteorological observations to ensure their reliability, and backward trajectory analyses are conducted using multiple meteorological inputs, including WRF, the Global Data Assimilation System (GDAS), and the Global Forecast System (GFS) datasets. By systematically comparing trajectory results derived from different meteorological resolutions, this study aims to elucidate the sensitivity of PM2.5 transport pathways to meteorological forcing and to clarify the relative contributions of local emissions and regional transport under southeast monsoon conditions. The findings are expected to provide a more robust scientific basis for understanding Jakarta's air pollution dynamics and to support the development of integrated, cross-regional air quality management strategies.

2. METHODOLOGY

2.1 Data

This study uses several datasets to analyze and identify the sources of PM2.5 pollution in DKI Jakarta during 2023. These datasets include Air Quality Index (AQI) data, meteorological observations, and atmospheric modeling data.

- Air quality index (AQI) data
  The AQI and $PM_{2.5}$ concentration data were obtained from AirNow, which provides hourly monitoring of $PM_{2.5}$ and other pollutants. These data were used to observe fluctuations in $PM_{2.5}$ levels across different regions of Jakarta. These data were collected from two monitoring stations in Jakarta (Central Jakarta and South Jakarta). The data can be downloaded from this link: https://www.airnow.gov/international/us-embassies-and-consulates/
- Weather observation data
  Weather parameters, including temperature, wind speed, humidity, and atmospheric pressure, were obtained from Ogimet (https://www.ogimet.com/gsynres.phtml.en), which provides meteorological data for model verification. These data were used to compare model outputs with observed meteorological conditions. Weather data, including precipitation and wind speed, were also obtained from the Meteorological, Climatological, and Geophysical Agency (BMKG) of Indonesia (https://dataonline.bmkg.go.id/). The meteorological stations used were Tanjung Priok, Soekarno-Hatta, and Kemayoran.
- Global forecast system (GFS) data
  The GFS dataset, accessed through the National Centers for Environmental Prediction (NCEP) (https://rda.ucar.edu/datasets/ds084.1/), was used as initial conditions for the WRF model. This dataset includes global atmospheric variables, such as temperature, wind speed, and humidity.
- Global data assimilation system (GDAS)
  GDAS data supported HYSPLIT modeling by providing additional atmospheric variables for pollutant trajectory analysis. GDAS data can be downloaded from this link: https://www.ready.noaa.gov/archives.php

2.2 Methodology

The research methodology employed a combination of advanced meteorological modeling and trajectory analysis to trace the sources of $PM_{2.5}$ in DKI Jakarta from July 4 to 9, 2023. The Weather Research and Forecasting (WRF) model was used to simulate atmospheric conditions in the region. WRF is a widely used, high-resolution numerical weather prediction model that can simulate weather phenomena locally with remarkable detail (Skamarock et al., 2019). For this study, the model domain was configured with two resolutions: a primary domain with a 9 km resolution and a nested domain with a finer 3 km resolution (see Figure 1). The nested domain enabled more detailed simulations of local atmospheric processes, which are critical for accurately modeling the dispersion and concentration of $PM_{2.5}$ in the urban environment of Jakarta (Zhao et al., 2021). The model's finer resolution provided a more precise representation of smaller-scale atmospheric dynamics. To enhance the representation of atmospheric processes over Jakarta, a tropical maritime region, the WRF model was configured using physical parameterization schemes that are widely applied and validated for tropical environments. The model employed the Kain-Fritsch cumulus parameterization to represent sub-grid scale convective processes, the WSM microphysics scheme to simulate cloud and precipitation processes, the Yonsei University (YSU) planetary boundary layer scheme to describe turbulent mixing in the lower atmosphere, and the Noah land surface model to represent land–atmosphere interactions. These parameterization schemes have been commonly used in tropical and urban meteorological studies and have demonstrated reasonable performance in simulating near-surface meteorological variables, including wind fields, under convective conditions (Skamarock et al., 2019; Zhao et al., 2021). The selection of these schemes is particularly relevant for Jakarta, where strong convection, high humidity, and complex boundary-layer dynamics dominate atmospheric conditions.

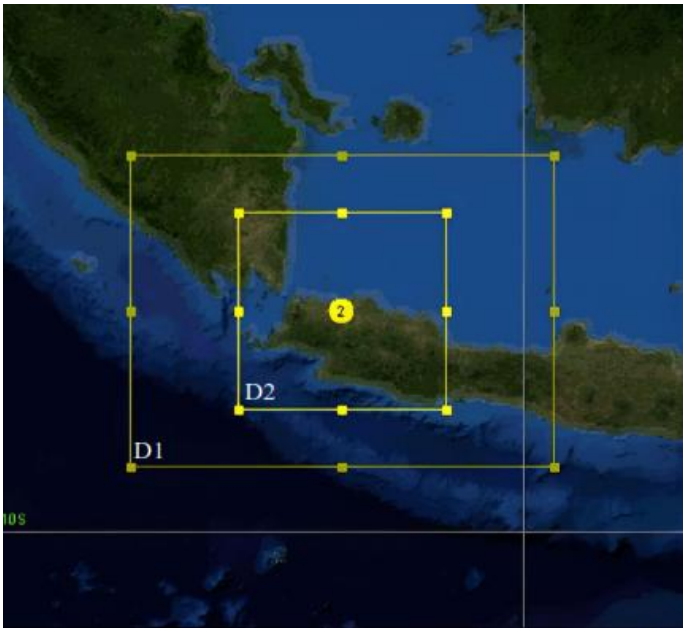


Figure 1. WRF Model Domain Setup showing the primary domain (D1 - 9 km resolution) and nested domain (D2 - 3 km resolution) for simulating PM2.5 dispersion in DKI Jakarta

Meteorological data from three local weather stations (Soekarno-Hatta, Kemayoran, and Tanjung Priok) were used to validate the WRF model. These stations provided observational data for temperature, humidity, wind speed, and atmospheric pressure, allowing for a direct comparison with the model's outputs. Several statistical methods were used to assess the model's performance, including the Pearson correlation coefficient, Root Mean Square Error (RMSE), and relative bias. The Pearson correlation coefficient, used to evaluate the linear relationship between observed and simulated data, was calculated using the formula.

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

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^{n}(x_i - y_i)^2} \tag{2}$$

$$RB = \frac{\sum_{i=1}^{n}(x_i - y_i)}{N} \tag{3}$$

Where x_i and y_i represent the observed and predicted values, respectively, and n is the number of data points. RMSE was calculated to measure the deviation between observed and model-predicted values, with smaller RMSE values indicating higher model accuracy. Additionally, relative bias was calculated to assess the model's tendency to overestimate or underestimate observed values. These statistical methods ensured that the WRF model accurately represented Jakarta's meteorological parameters during the study period.

In addition to verifying meteorological parameters like temperature, humidity, pressure, and wind speed, the model's wind direction was specifically verified using the Lavdas method. This method is employed to assess the accuracy of wind direction predictions in numerical models. It divides the wind direction into eight sectors (northeast, east, southeast, south, southwest, west, northwest, and north) representing the compass points. The Lavdas method compares the predicted wind direction against the observed data, categorizing the results into four groups: "Hit", "Near Miss to Right", "Near Miss to Left", and "Missed". A "Hit" occurs when the predicted wind direction matches the observed direction within the same sector. A "Near Miss to Right" means the predicted direction is one sector to the right of the observed direction, while a "Near Miss to Left" indicates the predicted direction is one sector to the left. "Missed" occurs when the predicted direction is more than one sector away from the observed direction. This classification helps quantify the model's ability to predict wind direction accurately (Pratama et al., 2025).

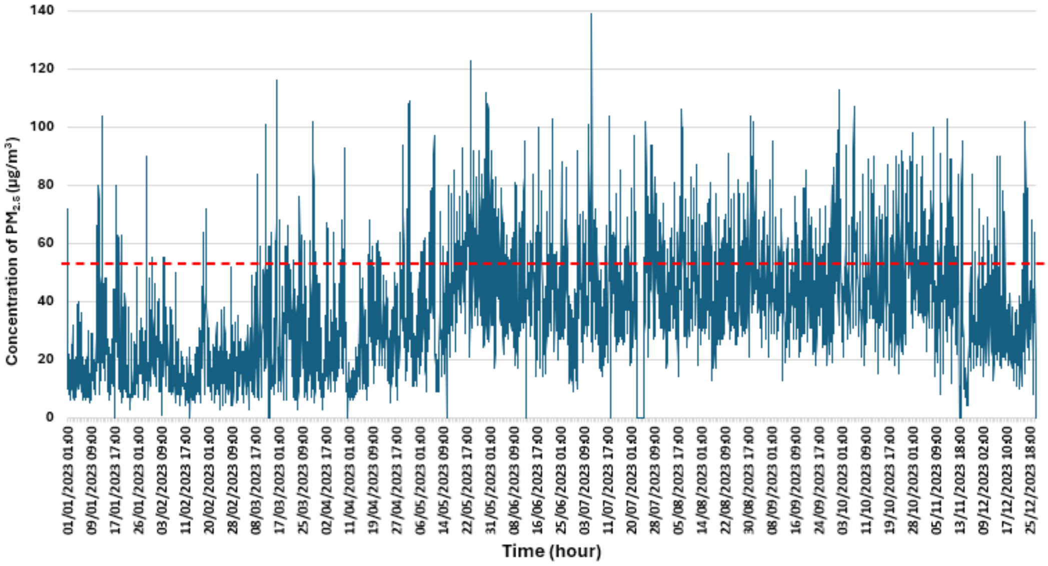
The HYSPLIT (Hybrid Single-Particle Lagrangian Integrated Trajectory) model was used to trace the origin and movement of PM2.5 particles across Jakarta. HYSPLIT is a widely recognized model for simulating the dispersion and transport of air pollutants and has been extensively used for trajectory analysis in environmental studies (Nurlatifah et al., 2025; Stein et al., 2015). This study's model was initialized using meteorological data from the WRF model, GDAS (Global Data Assimilation System), and GFS (Global Forecast System). The HYSPLIT model was run 10 meters above the ground level, as this altitude closely represents the atmospheric layer directly affecting human health and pollutant dispersion (Draxler & Hess, 2018). The backward trajectory simulations provided insight into the sources and movement patterns of $PM_{2.5}$ particles in Jakarta.

The analysis was also supported by considering meteorological factors that influence the dispersion of $PM_{2.5}$, including long-range transport (LRT). The GFS and GDAS datasets were also utilized to model the long-range transport of PM2.5, a phenomenon in which pollutants travel over long distances, often exceeding 100 km, influenced by prevailing wind patterns (Kim et al., 2015). Combining these datasets allowed for a comprehensive understanding of the various factors contributing to $PM_{2.5}$ pollution in Jakarta.

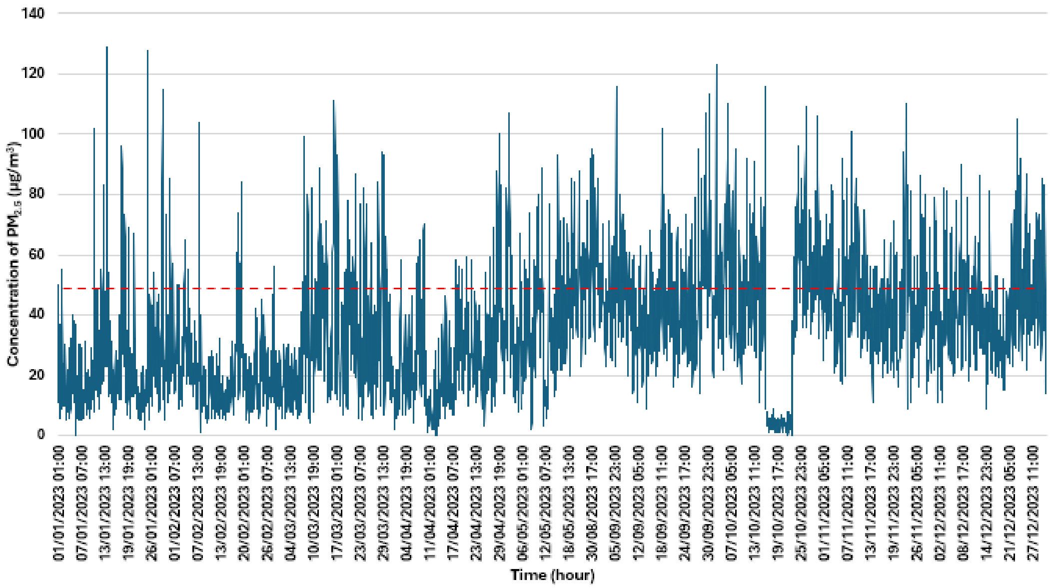
3. RESULTS

3.1 Analysis of Air Quality in DKI Jakarta

The air quality in DKI Jakarta throughout 2023 exhibited alarming trends, with significant periods of $PM_{2.5}$ pollution that raised concerns regarding public health and the environment. According to Indonesian regulations, a day is considered polluted if the $PM_{2.5}$ concentration exceeds 55 μg/m³. As shown in Figure 2, the analysis of hourly PM2.5 concentrations in both Central Jakarta and South Jakarta reveals fluctuations in pollution levels over the months.



(a) Central Jakarta



(b) South Jakarta

Figure 2. Hourly PM2.5 concentrations in Central and South Jakarta in 2023. The red line indicates the ambient air quality standard in Indonesia (55 μg/m³), with several instances exceeding this threshold

The highest pollution levels occurred in May, July, August, and October, with July to October recording the most polluted days. In contrast, February had the lowest levels of $PM_{2.5}$ pollution, showing a decrease in polluted hours, which likely reflects seasonal variations, the wet season (December – January – February), and the dry season (June – July – August) in

Jakarta. Overall, the data shows that approximately 17.57% of the days in Central Jakarta and 16.59% of the days in South Jakarta experienced pollution levels exceeding the 55 μg/m³ threshold (Indonesian Standard), indicating a significant portion of the year was marked by unhealthy air quality. Figure 2 presents the daily fluctuations of $PM_{2.5}$ concentrations in Central and South Jakarta. In Central Jakarta, the most polluted hours occurred in July and October, with about 270 hours or 36.29% of the total hours marked as polluted. May and August followed with 218 hours, or 29.30% of the hours in those months, indicating a peak in pollution levels likely associated with seasonal weather patterns and heightened human activity, such as increased vehicular emissions and industrial processes (Suryani, 2010).

The data from South Jakarta mirrored this trend, with July and October again being the months with the highest number of polluted hours (211 hours, or 28.36% of the month). Conversely, February exhibited the lowest pollution levels, with only 19 hours of polluted air, showing a marked improvement in air quality during that month. Figure 2 also shows that July has the highest concentration throughout 2023.The AQI values (see figure 3), based on $PM_{2.5}$ concentrations, further show the severe impact on air quality. The high AQI levels during the polluted months indicate that the air quality in Jakarta frequently falls within the "Unhealthy" to "Very Unhealthy" categories, which poses significant health risks for the population, particularly for sensitive groups such as children, the elderly, and individuals with pre-existing respiratory or cardiovascular conditions (Kurniawati et al., 2017). In July, $PM_{2.5}$ levels reached as high as 139 μg/m³, more than 27 times the WHO-recommended daily limit of 5 μg/m³, confirming that Jakarta faced significant pollution challenges throughout the year.

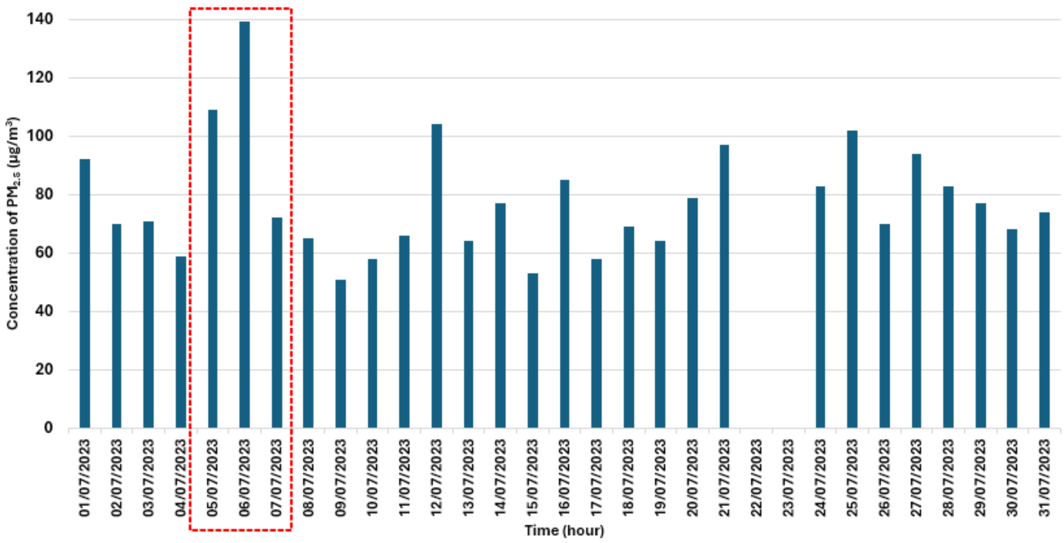


Figure 3. PM2.5 concentrations on 6 July 2023, in Central Jakarta, indicating "Very Unhealthy" air quality

Figure 3 highlights explicitly the peak of pollution on 6 July 2023, with $PM_{2.5}$ levels reaching 139 μg/m³ in Central Jakarta, which coincides with the most severe air quality condition during the study period. This peak concentration aligns with higher levels of traffic, industrial emissions, and possible agricultural burning in neighboring regions, which are common contributors to high $PM_{2.5}$ concentrations in Jakarta. The severe air quality on this day underscores the need for timely interventions to address pollution from both local and regional sources. In addition to the direct human health impacts, such high concentrations of

PM2.5 have serious environmental consequences. The persistence of fine particles in the atmosphere contributes to reduced visibility and the formation of haze, affecting the aesthetic and functional quality of the urban environment. Furthermore, the deposition of $PM_{2.5}$ into surfaces can lead to long-term damage to vegetation, buildings, and water bodies (Sibarani et al., 2021).

3.2 Verification of WRF Model

Verifying the WRF model outputs plays a crucial role in assessing the model's accuracy in simulating the meteorological conditions in Jakarta. This is particularly important as accurate weather data is essential for modeling air quality and the dispersion of pollutants such as $PM_{2.5}$. The results are presented in Table 1 and Figure 4, summarizing the model's predictive accuracy and providing a detailed analysis of the discrepancies between the observed and simulated values.

Table 1. Statistical comparison of observed and simulated wind speed, temperature, and humidity for July 4–9, 2023, at three Jakarta stations (Soekarno Hatta (I), Kemayoran (II), and Tanjung Priok (III))

Parameter	Correlation			Relative Bias			RMSE			Average		
	I	II	III	I	II	III	I	II	III	I	II	III
Temperature	0,7 p-value:0,000	0,67 p-value:0,000	0,52 p-value:0,000	-0,36	-1,57	-1,52	1,84	2,23	2,62	27,23	28,45	28,40
Humidity	0,51 p-value:0,000	0,57 p-value:0,00	0,55 p-value:0,000	-3,74	-0,96	-2,89	10,8	8,12	8,33	77,48	81,21	78,39
Pressure	0,48 p-value:0,00	0,5 p-value:0,00	0,49 p-value:0,000	-2,69	-2,85	-2,90	3,21	3,23	3,25	1007,7	1010,4	1010,6
Wind speed	0,37 p-value:0,000	0,13 p-value:0,154	0,45 p-value:0,000	0,84	1,65	0,67	1,77	2,45	2,13	2,64	1,79	0,99

*Number of data: 120 for stations I, II, and III and all parameters; and p-value for most of parameters is less than 0,05 (statistically significant between WRF and observed data)

The correlation coefficient (r) values in Table 1 reveal the linear relationship between the simulated and observed data. For temperature, the correlation ranged from 0.52 at Tanjung Priok to 0.7 at Soekarno-Hatta, indicating a moderate to strong relationship between the model and observations. These values suggest that the WRF model captures the temperature trends well, with stronger agreement at Soekarno-Hatta. A correlation coefficient of 0.7 is typically considered a strong correlation, indicating that the model provides a good approximation of temperature at this station. The humidity verification shows a similar trend, with correlation coefficients ranging from 0.51 to 0.57, which is slightly lower than the temperature but still indicates a reasonable level of agreement between the model and observations. The highest correlation for humidity was observed at Kemayoran (0.57), suggesting that the model simulated humidity patterns more accurately at this location. However, the correlation coefficients for pressure and wind speed were relatively weaker. For pressure, the correlation ranged from 0.48 to 0.5, indicating a moderate relationship. In contrast, the wind speed showed a notably weaker correlation, ranging from 0.13 to 0.45. However, p-values of wind speed greater than 0,05 (p-value > 0,05) indicate that it isn't statistically significant. This lower correlation for wind speed suggests that the model struggles more to simulate wind dynamics in Jakarta accurately, likely due to complex local topography and wind variability in urban environments (Han et al., 2020).

The RMSE values, which quantify the model's prediction errors, offer valuable insights into the model's performance. For temperature, the RMSE values ranged from 1.84°C to 2.62°C, suggesting that the model predicts temperature with relatively high accuracy, especially at Soekarno-Hatta, where the error is lowest (1.84°C). This small error indicates that temperature was one of the better-simulated parameters in the WRF model. For humidity, RMSE values ranged from 8.12% to 10.8%, again reflecting a reasonable model performance, particularly at Kemayoran, where the model's error was smaller. In contrast, pressure and wind speed had higher RMSE values, particularly for wind speed, with errors as significant as 2.45 m/s at Kemayoran. These RMSE values for wind speed suggest that the WRF model faces greater challenges in accurately simulating wind conditions in Jakarta. Relative bias values further confirm the model's tendency to overestimate or underestimate specific parameters. For temperature, the relative bias values were negative across all stations, ranging from -1.52 to -0.36, indicating that the WRF model generally underestimates temperature compared to the observed values. This is consistent with the RMSE results, where the model slightly underpredicted the temperature at most stations. On the other hand, the relative bias for wind speed was positive, particularly at Soekarno-Hatta, where the model overestimated wind speeds by 0.84 m/s, as shown in the bias values. This overestimation may be due to the model's limitations in accurately representing local wind dynamics, especially during periods of calm winds. For pressure and humidity, the relative bias values were also negative, indicating that the model slightly underestimates these parameters at all stations.

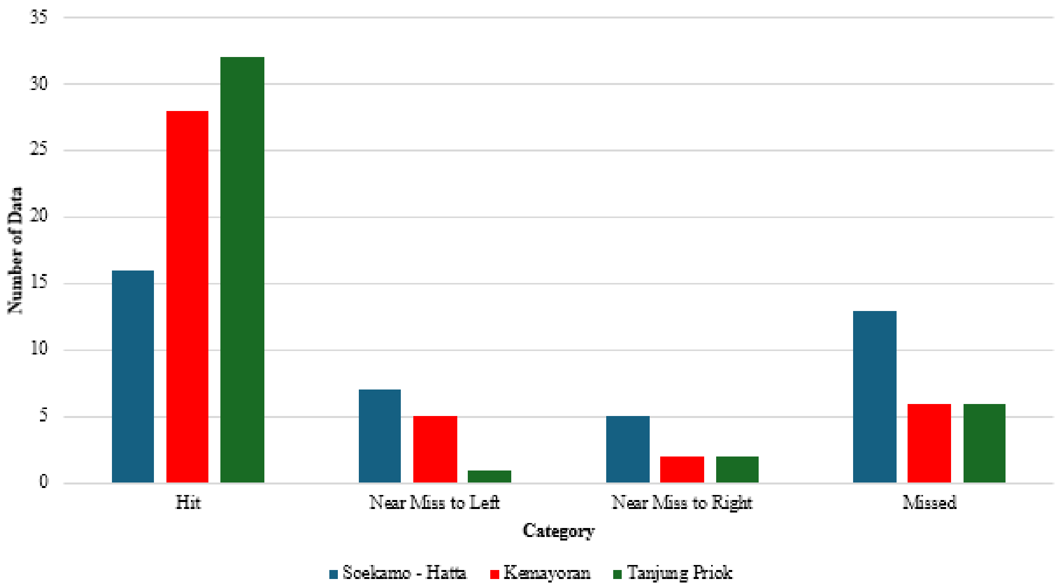
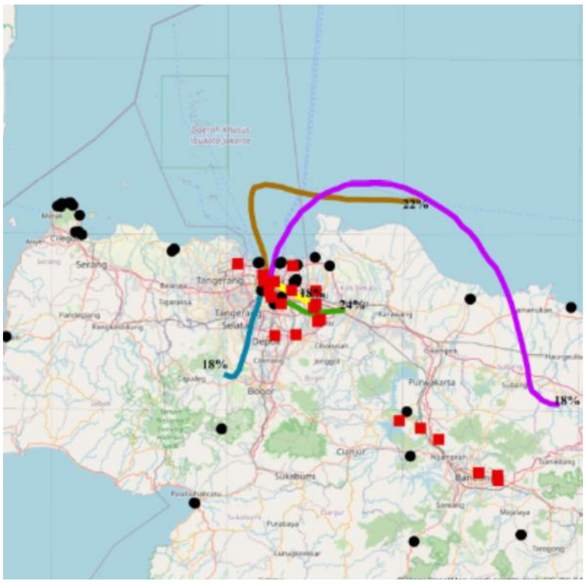


Figure 4. Wind direction verification for the WRF model at Soekarno-Hatta, Kemayoran and Tanjung Priok stations

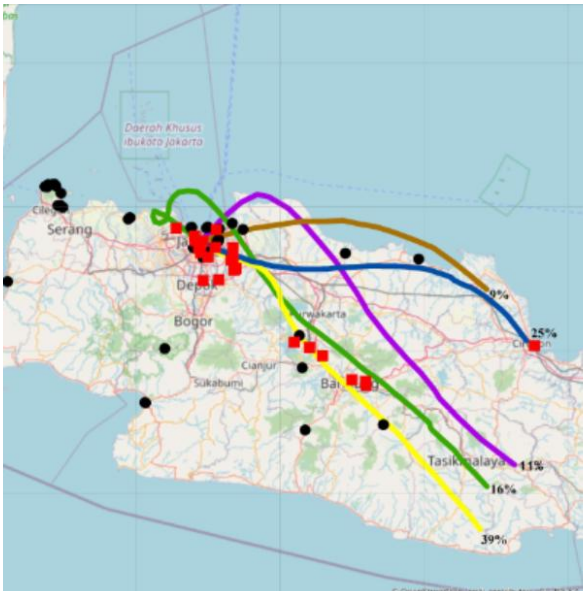
Figure 4 presents the verification of wind direction simulated by the WRF model, compared with observed data from three meteorological stations in Jakarta: Soekarno-Hatta, Kemayoran, and Tanjung Priok. Wind direction is a critical parameter for simulating pollutant dispersion, particularly in the HYSPLIT model, which tracks the backward trajectories of air pollutants. The accuracy of wind direction predictions directly influences the reliability of HYSPLIT's ability to identify pollutant sources and trace their movement through the atmosphere. The wind direction verification for Soekarno-Hatta station showed the highest accuracy, with 72% of the simulated wind directions classified as "Hit." This suggests that the WRF model accurately predicted the prevailing wind patterns at this station. Conversely, Kemayoran and Tanjung Priok stations had lower "Hit" percentages, 60% and 58%, respectively than Soekarno Hatta. Overall, the WRF model can detect wind direction well (moderate to strong accuracy) from observation data, as shown by the number of "Hit" events being more than others.

3.3 Backward Trajectory of $PM_{2.5}$ in Jakarta

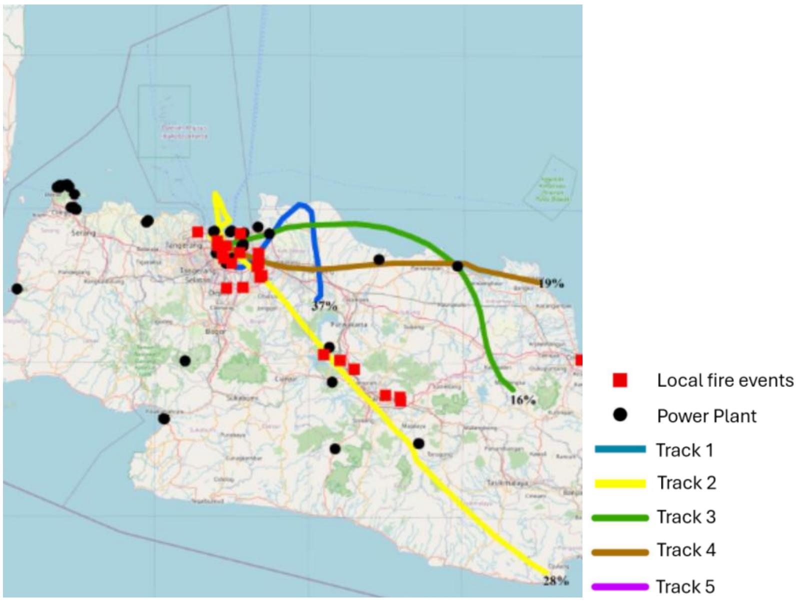
The backward trajectory analysis of $PM_{2.5}$ concentrations over Jakarta from 4–9 July 2023 provides insights into the sources and transport pathways of delicate particulate matter affecting the region. Using three meteorological datasets with different spatial resolutions (WRF (3 km), GDAS (54 km), and GFS (27 km)), the simulations (Figure 5) consistently revealed that the dominant air mass trajectories carrying $PM_{2.5}$ into Jakarta originated primarily from the east and southeast. The analysis identified that the highest contributions came from Trajectory 3 (Green) in the WRF dataset (24%), Trajectory 2 (yellow) in GDAS (39%), and Trajectory 1 (yellow) in GFS (37%), highlighting that while there are differences across datasets, the overall directional pattern remained consistent from southeast.



(a) WRF



(b) GDAS



(c) GFS Data

Figure 5. Backward trajectory of PM2.5 in Jakarta with different meteorological data input

The trajectories overlapped with known emission sources such as power plants, and local fire events, including residential and marketplace fires in East and South Jakarta, as well as in parts of West Java, suggesting that long-range and local contributions simultaneously exacerbate Jakarta's pollution burden. Furthermore, the presence of the southeast monsoon during the study period intensified the persistence of pollutants in the lower atmosphere due to drier meteorological conditions, which reduced the dispersion rate and prolonged the residence time of $PM_{2.5}$ over the capital. This phenomenon aligns with previous studies reporting that seasonal monsoonal winds can significantly influence pollutant transport in Southeast Asia (e.g., Lestari et al., 2019; Kusumaningtyas & Aldrian, 2016). The comparison across datasets also underscored the critical role of model resolution: the high-resolution WRF data produced shorter and more localized trajectories compared to the coarser GDAS and GFS, which extended further and represented larger spatial domains. This discrepancy illustrates how finer resolution meteorological data can capture mesoscale atmospheric dynamics more accurately, while coarser global datasets may provide broader but less detailed insights. Importantly, these findings emphasize that Jakarta's air quality is not solely a result of internal emissions but is also heavily shaped by transboundary transport processes, particularly under specific seasonal wind regimes. The implications are significant for air quality management, as policies targeting only local emission reductions may be insufficient if external sources are not considered in regional frameworks. Moreover, the persistence of elevated $PM_{2.5}$ throughout July 2023, as supported by the concurrent concentration data (Figures 2 and 3), underscores the health risks faced by the population when meteorological conditions favor pollutant accumulation. Overall, the results highlight the interplay between meteorological drivers, emission sources, and transport processes in shaping urban air pollution in Jakarta, providing an essential scientific basis for regional air quality policy and cross-boundary management strategies.

4. DISCUSSION

The robustness of trajectory-based source identification is fundamentally governed by the accuracy of the meteorological fields used to drive the transport model. Verification of the WRF simulations demonstrates that temperature, humidity, and wind direction are simulated with reasonable skill, whereas wind speed exhibits lower correlation coefficients and statistically insignificant correlations (p-value > 0.05) at several stations. This performance asymmetry has important implications for interpreting the HYSPLIT backward trajectories. Wind direction is the primary determinant of horizontal air mass displacement and therefore exerts dominant control on the orientation of transport pathways. In contrast, wind speed uncertainty mainly affects trajectory length, travel time, and residence duration rather than directional consistency. Consequently, while uncertainties remain regarding the precise upstream distance and timing of PM2.5 transport, the dominant transport sectors identified in this study can be interpreted with a relatively high degree of confidence. This interpretation is further supported by the consistency of trajectory directions obtained from independent meteorological inputs (WRF, GDAS, and GFS), indicating that the inferred source regions are controlled by synoptic- and mesoscale flow patterns rather than by model-specific wind speed biases (Draxler & Hess, 2018; Stein et al., 2015).

Backward trajectory analysis consistently indicates that $PM_{2.5}$ influencing Jakarta during the July 2023 pollution episode was predominantly transported from the east and southeast. These transport pathways intersect regions characterized by high anthropogenic emission density, including industrial complexes, coal-fired power plants, and documented local fire activity in eastern and southern Jakarta, as well as parts of West Java. Although this study does not employ chemical source apportionment techniques, the relative frequency of trajectory clusters provides a semi-quantitative measure of the influence of source regions. Trajectories originating from the southeast sector occur more frequently than those from other directions, suggesting a comparatively stronger contribution from emission sources located in that region. Similar trajectory-cluster-based interpretations have been widely adopted in atmospheric studies where speciated PM2.5 measurements are unavailable, allowing for inference of dominant source regions while acknowledging inherent uncertainties (Melinda & Nuryanto, 2023; Nurlatifah & Driejana, 2019). However, it should be emphasized that trajectory frequency does not directly represent emission strength or chemical contribution, as it neglects variations in source intensity, atmospheric transformation, and removal processes.

Meteorological conditions during July 2023 played a critical role in modulating PM2.5 accumulation over Jakarta. The dominance of the southeast monsoon during the dry season is associated with reduced precipitation, relatively stable boundary layer conditions, and weakened vertical mixing. These factors collectively suppress pollutant dispersion and enhance near-surface accumulation of fine particulate matter. Previous studies have shown that monsoonal circulation over Indonesia exerts strong control on aerosol transport and persistence, particularly during dry-season conditions when wet scavenging is minimal (Kusumaningtyas et al., 2018; Lestari et al., 2021). The present findings are consistent with this framework, indicating that extreme pollution episodes in Jakarta are strongly modulated by meteorological forcing and atmospheric stability rather than by emission variability alone.

A comparison of backward trajectories generated using meteorological fields with varying spatial resolutions highlights the sensitivity of trajectory characteristics to model resolution. High-resolution WRF outputs (3 km) yield shorter and more localized trajectories that better resolve mesoscale flow features relevant to the Jakarta metropolitan area, whereas coarser global datasets (GDAS and GFS) produce longer trajectories that extend further upstream. Despite these differences, the convergence of dominant transport directions across datasets enhances confidence in identifying major source regions. This multi-dataset comparison effectively serves as an implicit sensitivity assessment, demonstrating that the primary conclusions regarding transport pathways are robust to uncertainties in wind speed representation and meteorological resolution (Kim et al., 2015; Stein et al., 2015).

Uncertainty is an inherent component of trajectory-based analyses and must be explicitly considered. Limitations associated with the WRF wind speed simulation, the spatial resolution of meteorological inputs, and the assumption of passive tracer transport introduce uncertainty into the reconstructed air mass histories. These uncertainties primarily affect trajectory length, travel time, and vertical motion but are less likely to alter dominant horizontal transport pathways. Explicit discussion of these limitations enhances the transparency and interpretability of the results. Future work could further reduce uncertainty through ensemble trajectory approaches, explicit wind speed perturbation experiments, or the application of coupled chemistry–transport models that can simulate chemical transformation and deposition processes.

The results of this study have direct implications for air quality management in Jakarta. The dominance of $PM_{2.5}$ transport from the eastern and southeastern sectors indicates that mitigation strategies focusing exclusively on emissions within Jakarta are unlikely to be sufficient during dry-season pollution episodes. Targeted emission controls in industrial zones and coal-fired power plants located east of Jakarta, combined with improved management of local fire incidents, may yield substantial air quality benefits. Furthermore, strengthened inter-provincial coordination between Jakarta and the surrounding regions is essential to address transboundary pollution transport. Incorporating monsoon-aware strategies, such as seasonal emission reduction measures and early warning systems during forecasted stagnation conditions, could further mitigate population exposure during extreme pollution events.

5. CONCLUSIONS

This study investigated the sources and transport pathways of PM2.5 in Jakarta during the extreme pollution episode in July 2023, utilizing an integrated WRF–HYSPLIT modeling framework supported by observational data. The results demonstrate that PM2.5 concentrations during this period were strongly influenced by air mass transport from the east and southeast, intersecting regions characterized by intensive industrial activities, power generation facilities, and local fire events. The verification of the WRF model indicates satisfactory performance in simulating wind direction, which provides confidence in identifying the dominant transport pathways. However, wind speed simulations exhibit lower and statistically insignificant correlations. This limitation implies that the precise spatial extent and travel distance of the identified source regions carry a degree of uncertainty; however, the consistency of transport directions across multiple meteorological inputs suggests that the main source sectors identified in this study are robust.

Beyond summarizing the results, this study makes several novel contributions. It provides an event-based analysis of the most severe PM2.5 pollution episode in Jakarta during 2023, applies a multi-resolution and multi-dataset meteorological framework to assess trajectory robustness, and integrates WRF model verification with trajectory-based source identification under southeast monsoon conditions. The use of multiple meteorological inputs (WRF, GDAS, and GFS) provides an implicit assessment of uncertainty in trajectory analysis, thereby strengthening confidence in the overall interpretation. The findings have clear policy implications. Effective mitigation of PM2.5 pollution in Jakarta should prioritize targeted emission controls in industrial zones and power generation facilities located east and southeast of the city, improve the management of local fire incidents, and strengthen inter-regional cooperation with surrounding provinces to address transboundary pollution, particularly during the dry season. Seasonal air quality management strategies that incorporate meteorological forecasting, such as early warning systems during periods of atmospheric stagnation, could further reduce population exposure during extreme events.

ACKNOWLEDGMENT

The authors would like to express their sincere gratitude to the Program Studi Sains Atmosfer dan Keplanetan, Institut Teknologi Sumatera (ITERA), for providing the facilities and support that made this research possible.

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