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Journal of Engineering Science and Technology Management

| ISSN (Online) 2828 -7886 |



Article

Analysis of Air Pollution Trajectory Using the HYSPLIT Model

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DOI: 10.31004/jestm.v5i2.424

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ARTICLE INFORMATION

Volume 5 Issue 2
Received: 10 Augustus 2025
Accepted: 29 September 2025
Publish *Online*: 30 September 2025
Online: at <https://JESTM.org/>

Keywords

Air Pollution
HYSPLIT
Forward Trajectory
Industrial Emission
Transboundary Transport

ABSTRACT

The growth of industrial activities has contributed significantly to the increase in air pollutant emissions, adversely affecting human health and environmental quality. Understanding the direction and potential dispersion of air pollutants is therefore a crucial aspect of air pollution control efforts, particularly for mitigating transboundary and transregional impacts. This study aims to analyze the movement trajectories of air pollutants released from industrial stacks using the Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model. Forward trajectory simulations were conducted for a duration of 240 hours (10 days) using meteorological data from the Global Forecast System (GFS). The emission source was assumed to be located in the Perawang industrial area, with a stack height of 100 meters above ground level. The simulation results indicate that during the dry season (East Monsoon), the dominant direction of air mass movement tends to be northward to northeastward, crossing the Malacca Strait and potentially reaching regions of Malaysia, Thailand, Vietnam, and southern China. These findings suggest a significant potential for long-range and transboundary transport of air pollutants, highlighting the need for strengthened industrial emission control and enhanced regional cooperation in air pollution management.

1. Introduction

Air pollution remains a critical global environmental challenge with profound implications for public health, climate interactions, and ecosystem stability. The World Health Organization estimates that ambient air pollution contributes to millions of premature deaths annually, primarily due to cardiovascular and respiratory diseases associated with fine particulate matter (PM_{2.5}) and gaseous pollutants. In rapidly industrializing regions of Southeast Asia, industrial stack emissions constitute a substantial source of sulfur dioxide (SO₂), nitrogen oxides (NO_x), and particulate matter, which may undergo atmospheric transport far beyond their points of origin.

The dispersion of industrial emissions is strongly governed by synoptic-scale circulation, atmospheric stability, and seasonal meteorological variability. In equatorial regions such as Sumatra, seasonal contrasts between wet and dry periods significantly influence atmospheric mixing height, precipitation scavenging, and pollutant residence time. During the dry season, reduced wet deposition and enhanced atmospheric persistence may facilitate long-range pollutant transport, increasing the likelihood of regional or transboundary impacts.

Trajectory-based atmospheric modeling has become a fundamental tool for investigating pollutant transport pathways. The Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model, developed by the National Oceanic and Atmospheric Administration (NOAA), is widely applied in studies of transboundary haze, wildfire smoke dispersion, and long-range pollutant transport. However, despite its extensive global application, region-specific trajectory assessments in Riau Province, Indonesia an area characterized by expanding industrial development and recurrent air quality concerns remain notably limited in peer-reviewed literature. More importantly, previous applications in Indonesia have predominantly focused on short- to medium-range trajectory simulations (typically 24-120 hours), primarily in the context of biomass burning and regional haze events. Extended forward trajectory simulations reaching 240 hours (10 days), particularly originating from fixed industrial stack sources, have not been systematically examined in this region. The absence of such

long-duration simulations constrains understanding of the full spatial extent and persistence of industrial emission influence. Additionally, dry-season-specific trajectory clustering and dominant pathway identification remain underexplored, leaving uncertainty regarding potential long-range or cross-boundary transport mechanisms.

This study addresses these critical gaps by conducting an extended 240-hour forward trajectory analysis from a stationary industrial emission source in Riau during the dry season. By integrating high resolution meteorological inputs and multi-day trajectory simulations.

2. Literature Review

Air pollution has been widely recognized as a major environmental and public health concern. The World Health Organization identifies ambient air pollution as one of the leading environmental risk factors contributing to global morbidity and premature mortality. Recent studies emphasize the combined influence of anthropogenic emissions and atmospheric processes in determining pollutant concentration, transformation, and health impacts (Zhang & He, 2020). While early foundational research established the health risks of particulate matter and gaseous pollutants, contemporary investigations increasingly focus on atmospheric transport dynamics and regional-scale pollution interactions.

In Southeast Asia, transboundary air pollution has become a critical regional issue, formally acknowledged through the ASEAN Agreement on Transboundary Haze Pollution. Most regional studies have concentrated on biomass burning and haze episodes, demonstrating that synoptic-scale wind circulation can transport pollutants across national boundaries. However, limited attention has been given to the potential regional transport of emissions from continuous industrial point sources, particularly in rapidly developing provinces such as Riau, Indonesia.

Long-range transport (LRT) of air pollutants is governed by atmospheric advection, turbulence, and boundary layer dynamics. The Atmospheric Boundary Layer (ABL) plays a central role in determining vertical mixing, dilution, and residence time of pollutants. Seasonal variability, especially during dry periods in equatorial regions, may enhance pollutant persistence due to reduced wet

deposition and altered mixing height conditions. Despite the importance of these mechanisms, their integration into regional industrial emission assessments in Indonesia remains limited.

Trajectory-based atmospheric modeling has become a widely accepted approach for investigating pollutant transport pathways. The Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model, developed by the National Oceanic and Atmospheric Administration, has been extensively applied in studies of transboundary haze, severe particulate pollution events, and long-range transport analysis (Stein et al., 2015; Chen et al., 2017). However, most prior applications focus on short- to medium-term simulations (24–120 hours), with limited studies extending trajectory analysis to 240 hours for stationary industrial sources in equatorial Southeast Asia.

From an environmental health perspective, understanding transport pathways is essential within the exposure pathway framework, which links emission sources, environmental transport, exposure routes, and health outcomes. Without spatially explicit trajectory analysis, the regional influence and potential exposure zones of industrial emissions remain uncertain.

While atmospheric transport modeling is well established globally, there remains a notable research gap in long-duration, dry-season trajectory analysis of industrial emissions in Riau. Addressing this gap is essential for strengthening regional air quality management and evidence based environmental governance.

3. Research Methodology

Atmospheric modeling approach to analyze the directional movement and long-range transport patterns of air masses originating from an industrial emission source in Riau, Indonesia. Forward air mass trajectories were simulated using the Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model Version 4, developed by the National Oceanic and Atmospheric Administration (NOAA). The model was executed through the READY (Real-time Environmental Applications and Display sYstem) platform.

Meteorological input data were obtained from the Global Forecast System (GFS) archive provided by NOAA. The GFS dataset used in this study had a spatial resolution of $0.25^\circ \times 0.25^\circ$ and a temporal resolution of 3 hours,

enabling regional-scale atmospheric representation with sufficient synoptic accuracy. The selection of 0.25° resolution was intended to improve spatial representation compared to coarser datasets, thereby reducing trajectory uncertainty in equatorial regions.

3.1 Meteorological Data and Emission Source

Meteorological data used in this study were obtained from the Global Forecast System (GFS) dataset provided by the National Oceanic and Atmospheric Administration (NOAA). The GFS dataset was selected due to its global spatial coverage, high temporal resolution, and its widespread application in atmospheric transport and air mass trajectory modeling studies. The trajectory simulation was initiated on 19 August 2025, representing dry-season meteorological conditions in the study area. Forward trajectories were computed for a duration of 240 hours (10 days) to assess the potential long-range transport and spatial influence of air masses originating from the industrial emission source.

Table 1. Coordinates of Industrial Stack Emission Sampling Locations

Sampling Location	Coordinate Point
Industrial Stack 1	0.6933° N, 101.6195° E
Industrial Stack 2	0.6935° N; 101.6197° E

The study location was assumed to be situated in the Perawang industrial area, Riau Province, Indonesia. The pollution source was modeled as emissions released from industrial stacks with a height of 100 meters above ground level (AGL). Two source points were employed to represent variations in stack locations within the industrial area.

3.2 Data Analysis

Forward trajectory method was applied to project the movement of air masses forward in time from the source locations. The simulation duration was set to 240 hours, equivalent to 10 days, in order to evaluate the potential for medium- to long-range transport of air pollutants.

A total of two trajectories (number of trajectories = 2) were generated, originating from the same horizontal location and analyzed simultaneously to assess the consistency of air mass movement directions. The vertical motion

parameter employed in the simulation was the vertical velocity model. This parameter was selected because it is considered to more realistically represent vertical air mass movement, particularly under atmospheric conditions influenced by convection and turbulence.

The simulated trajectories were analyzed both spatially and temporally to identify the dominant directions of air mass movement from the emission sources. The analysis was conducted by examining daily (0-72 hours), intermediate (72-144 hours), and long-term (144-240 hours) trajectory patterns.

Trajectory altitude analysis was performed to evaluate whether the air masses remained within the atmospheric boundary layer or reached higher atmospheric layers. The interpretation of the results was linked to regional meteorological conditions, particularly the prevailing East Monsoon wind patterns during the simulation period.

4. Results and Discussion

The HYSPLIT forward trajectory simulations conducted in this study and discusses them in direct relation to the research objective, namely to identify the direction and potential long-range transport of air pollutants emitted from an industrial area in Perawang, Riau. The discussion is framed within the context of atmospheric transport theory and previous studies on monsoon-driven pollutant dispersion in Southeast Asia.

4.1 Temporal Characteristics of Pollutant Transport

Model simulations over a 240-hour period demonstrate a clear and consistent pattern of air mass movement originating from the assumed industrial emission sources in Perawang. During the simulation period of 19 August 2025, regional meteorological conditions were dominated by the dry-season monsoonal circulation, which strongly influenced the direction of air mass transport.

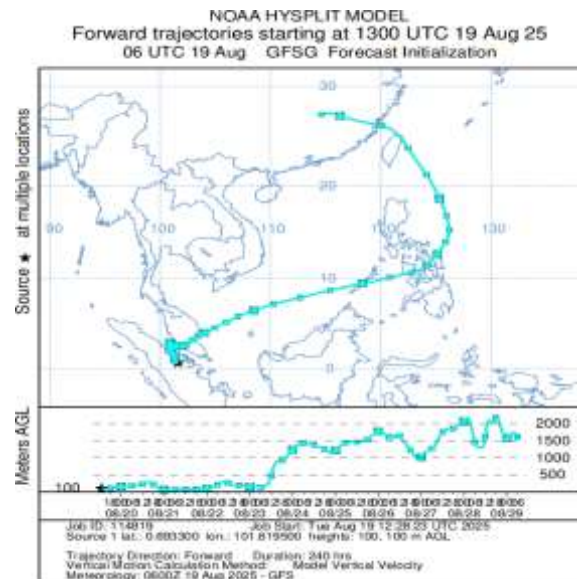


Figure. 1 Running Result HYSPLIT Forward Air Mass Trajectory

Based on HYSPLIT model result, the simulation indicate during the first 0–72 hours, the air mass moved predominantly toward the east to northeast, crossing the Malacca Strait and the Malaysian Peninsula toward the South China Sea. This pattern suggests the influence of strong regional wind circulation during the simulation period, which climatologically corresponds to the monsoonal dynamics in Southeast Asia in August. The relatively consistent initial movement indicates a potential for regional-scale transboundary pollutant transport during the early phase of release.

During the intermediate period (72–144 hours), the trajectory gradually shifted northward and northeastward, entering the central South China Sea and approaching southern Vietnam. The curved trajectory pattern indicates the influence of regional atmospheric pressure systems or pressure gradient changes that modified the direction of air mass advection. In the final phase of the simulation (144–240 hours), the air mass pathway turned further toward the north to northwest, approaching southern China. These findings suggest that within a 10-day time frame, air masses originating from a source in Sumatra have the potential to undergo long-range transport spanning thousands of kilometers from the initial location.

The vertical profile analysis reveals significant altitude dynamics throughout the simulation period. During the first 48 hours, the air mass remained relatively within the lower

layer (<500 meters AGL), indicating movement within the planetary boundary layer. This condition implies a greater potential impact on pollutant concentrations in the initial receptor regions due to limited vertical mixing. After approximately 72 hours, the trajectory showed a progressive increase in altitude, reaching 1500–2000 meters AGL, with altitude fluctuations persisting until the end of the simulation period. This increase indicates vertical lifting processes, either due to convection or synoptic-scale atmospheric dynamics, allowing pollutant transport into the free troposphere. At these altitudes, pollutants tend to experience wider dispersion and longer atmospheric residence times, thereby expanding the affected spatial coverage even though surface concentrations may decrease due to dilution processes.

Overall, the simulation results demonstrate the potential for cross-border pollutant transport from Sumatra toward Malaysia, Vietnam, and East Asian regions over medium- to long-term timescales. Although trajectory analysis does not directly represent pollutant concentrations or atmospheric chemical transformation processes, this approach provides strong indications of dominant air mass movement directions and potential emission dispersion pathways. Therefore, these findings support the hypothesis that emission sources in the study area may contribute to regional and transboundary air pollution phenomena, particularly during periods characterized by prevailing wind patterns that favor northeastward transport.

4.2 Implication for Regional Transboundary Air Pollution

The results of this study demonstrate that air pollutants emitted from the Perawang industrial area are not restricted to the local environment. Instead, under dry-season meteorological conditions, these pollutants have the potential to affect regions beyond national boundaries, including Malaysia, Thailand, Vietnam, and southern China. This finding underscores the importance of considering transboundary air pollution in the management of industrial emissions in Sumatra. The trajectory-based evidence obtained in this study supports the need for regional cooperation in air quality monitoring and emission control, particularly within the ASEAN region, where seasonal wind systems strongly influence pollutant transport pathways.

5. Conclusion

Trajectory-based atmospheric modeling provides valuable insights into the regional and transboundary implications of industrial air emissions. The findings of this study emphasize the importance of strengthening industrial emission control, enhancing continuous air quality monitoring, and promoting regional cooperation in air pollution management. Future studies are recommended to integrate trajectory analysis with dispersion and concentration modeling to better quantify the environmental and health impacts of industrial emissions from the Perawang area.

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