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Modeling Air Pollutant Dispersion in Urban Areas: A HYSPLIT-Based Analysis of PM2.5 Dynamics in Medan, Indonesia

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Abstract
Air pollution is a critical environmental challenge in urban areas, particularly developing regions like Medan, Indonesia. This study aims to analyze the dynamics of PM 2.5 dispersion, identify pollution sources, and assess the role of meteorological factors in influencing air quality. Using the HYSPLIT model, the research examines pollutant transport and dispersion over ten months, specifically focusing on a high-pollution episode in May 2024. The study integrates meteorological data and local air quality measurements to simulate forward and backward trajectories at multiple altitudes. The results reveal that PM 2.5 concentrations in Medan are driven by local emissions, such as transportation and industrial activities, and transboundary pollution from biomass burning in neighboring provinces. Higher altitudes capture the influence of regional winds, while localized sources and atmospheric turbulence dominate near-surface levels. Meteorological conditions, including wind patterns, temperature stability, and rainfall, significantly affect pollutant dispersion and accumulation. By leveraging advanced modeling tools and meteorological data, the study provides a robust framework for air quality management in urban environments. These insights contribute to the broader understanding of pollution dynamics and support evidence-based strategies to protect public health and the environment.
Keywords: *medan, HYSPLIT, wind, PM2.5*

Abstrak
Polusi udara merupakan tantangan lingkungan yang kritis di kawasan perkotaan, khususnya di wilayah berkembang seperti Medan, Indonesia. Penelitian ini bertujuan untuk menganalisis dinamika dispersi PM 2.5, mengidentifikasi sumber polusi, dan mengevaluasi peran faktor meteorologi dalam memengaruhi kualitas udara. Dengan menggunakan model HYSPLIT, penelitian ini mengkaji transportasi dan dispersi polutan selama periode sepuluh bulan, dengan fokus khusus pada episode polusi tinggi yang terjadi pada Mei 2024. Studi ini mengintegrasikan data meteorologi dan pengukuran kualitas udara lokal untuk mensimulasikan trajektori maju dan mundur pada berbagai ketinggian. Hasilnya menunjukkan bahwa konsentrasi PM 2.5 di Medan dipengaruhi oleh kombinasi emisi lokal, seperti aktivitas transportasi dan industri, serta polusi lintas batas akibat pembakaran biomassa di provinsi tetangga. Ketinggian yang lebih tinggi menangkap pengaruh angin regional, sedangkan level dekat permukaan didominasi oleh sumber lokal dan turbulensi atmosfer. Kondisi meteorologi, termasuk pola angin, stabilitas suhu, dan curah hujan, secara signifikan memengaruhi dispersi dan akumulasi polutan. Dengan memanfaatkan alat pemodelan canggih dan data meteorologi, penelitian ini menyediakan kerangka kerja yang kuat untuk manajemen kualitas udara di lingkungan perkotaan. Wawasan ini berkontribusi pada pemahaman yang lebih luas tentang dinamika polusi dan mendukung strategi berbasis bukti untuk melindungi kesehatan masyarakat dan lingkungan.
Kata Kunci: *medan, HYSPLIT, angin, PM2,5*

1. Introduction

Air pollution has become one of the most significant environmental challenges of the 21st century, particularly in urban areas experiencing rapid urbanization and industrialization (Callén, López, & Mastral, 2011; Insian, Yabueng, Wiriya, & Chantara, 2022; Jakovljević et al., 2018; Jamhari et al., 2021; Mohanraj, Solaraj, & Dhanakumar, 2011; Nisa'ul Khoir, M.Cc, Ahmad, & Nurhayati, 2020; Siudek, 2022). As the economic and social hub of Sumatera (Marlier et al., 2015; Nisa'ul Khoir et al., 2020), Medan faces increasing emissions of air pollutants from various sources, including transportation, industry, and infrastructure development. Pollutants such as PM 2.5, PM 10, carbon monoxide (CO), sulfur dioxide

(SO_2), and nitrogen dioxide (NO_2) are known to have serious impacts on human health, ecosystems, and overall quality of life. A study by Pereira and Fernandino (2019) highlights the critical importance of sustainable air quality management in developing cities, given its significant effects on public health and environmental quality.

As one of Indonesia's largest cities, Medan frequently experiences air pollution, including haze from forest fires in neighboring regions. This phenomenon affects local air quality and spreads to other areas through atmospheric mechanisms. In a global context, this challenge is exacerbated by climate change, which can alter weather patterns and atmospheric dynamics, as reported by Joshi and Visvanathan (2019). Therefore, a detailed analysis of the sources, dispersion patterns, and risks associated with air pollutants is essential to support data-driven decision-making in air quality management for urban areas like Medan.

A major issue in managing air quality in Medan is the lack of a comprehensive understanding of air pollutant dispersion patterns and identifying key emission sources. Most previous studies have focused on direct measurements of pollutant concentrations without analyzing the atmospheric transport dynamics that influence their distribution. Moreover, limited air monitoring infrastructure in the city poses challenges in identifying priority areas for emission control. To address these gaps, various scientific approaches have been employed to study and mitigate the impacts of air pollution, including atmospheric modeling and spatial analysis. These approaches enable deeper evaluations of how pollutants move and disperse on regional and local scales.

Atmospheric models such as the Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model have become highly relevant tools to address these challenges. HYSPLIT is designed to predict the movement and concentration of air pollutants by integrating meteorological data. The model combines Lagrangian and Eulerian approaches, allowing simulations of air parcel movements based on atmospheric dynamics and pollutant distributions within a spatial grid. A study by Apriani et al. (2022) demonstrated that HYSPLIT is highly effective in analyzing pollutant dispersion in geographically complex regions like Indonesia, influenced by various atmospheric phenomena, including monsoons and local turbulence.

In scientific literature, HYSPLIT has been widely used to study various air pollution phenomena, including haze from forest fires, industrial emissions, and transboundary transport (Chang et al., 2021; Ellrod, 2015; Stein et al., 2016; Su, Yuan, Fung, & Lau, 2015; Yang, Kalpakis, & Yesha, 2015). Mesjasz-Lech (2019) noted that this model enables more accurate identification of pollution sources, both local and regional while providing valuable insights for more effective emission control. This model has also been integrated with direct observational data to enhance the validity of analytical results. However, its application in the context of major cities in Indonesia, including Medan, still needs to be improved.

Previous studies using HYSPLIT have provided valuable insights into air pollutant dispersion patterns, but most of these studies were conducted in regions with geographical and atmospheric conditions different from Medan. For example, research by Erfani et al. (2019) in the West Asia region demonstrated that wind speed and local topography heavily influence pollutant movement patterns, emphasizing the importance of adapting the model to specific regional conditions. Therefore, applying HYSPLIT in Medan requires adjustments based on local characteristics such as dominant wind directions, humidity levels, and specific emission sources.

The main gap in the literature is the need for modeling specific to Medan that considers unique factors such as urbanization, local emission sources, and interactions with regional atmospheric phenomena. This study aims to bridge that gap by leveraging the HYSPLIT model to analyze air pollutant dispersion patterns in Medan. The analysis includes identifying major emission sources, evaluating environmental and health risks, and recommending data-driven air pollution mitigation strategies.

This research aims to comprehensively understand air pollutant dispersion patterns in Medan through HYSPLIT modeling. The study aims to identify pollutant sources, assess risks to public health and the environment, and develop effective mitigation strategies. The novelty of this research lies in its specific application to Medan, a region with unique atmospheric characteristics and emission sources. As such, this study is expected to significantly contribute to air quality management in major Indonesian cities and provide a strong foundation for data-driven decision-making in mitigating the impacts of air pollution.

2. Material and Methods

2.1 Research Framework

The research employs a structured framework to analyze air quality in Medan, utilizing the Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model. This approach combines meteorological data, advanced modeling techniques, and spatial analysis to investigate air pollution dynamics. The primary aim is to assess pollutants' dispersion and transport patterns while identifying their sources. The study focuses on particulate matter (PM 2.5) as a key pollutant due to its critical health implications. The methodology encompasses data collection, model configuration, and interpretation of results to provide actionable insights for air quality management.

2.2 Study Area and Period

The research was conducted in Medan, Indonesia, at a latitude of 3.59°N and a longitude of 98.68°E. Medan is the economic hub of Sumatra and is characterized by high industrial and transportation activity, contributing significantly to air pollution. The analysis focuses on the period from January to October 2024, with a particular emphasis on May 16, 2024, when PM 2.5 concentrations peaked. This temporal selection enables a detailed examination of pollution patterns during critical air quality episodes.

2.3 HYSPLIT Model Overview

The HYSPLIT model, developed by the National Oceanic and Atmospheric Administration (NOAA), is a hybrid atmospheric modeling system integrating Lagrangian and Eulerian approaches. The Lagrangian method tracks air parcel movements influenced by meteorological conditions, while the Eulerian approach calculates pollutant concentrations within a spatial grid. This combination allows dynamic pollutant transport and dispersion simulations over time (Apriani et al., 2022). HYSPLIT is widely recognized for its versatility in analyzing forward and backward trajectories, making it a powerful tool for source identification and projection of pollutant dispersion.

2.4 Data Sources

The study integrates multiple datasets to ensure robust modeling and analysis. Meteorological inputs, including wind speed, wind direction, atmospheric pressure, and temperature, were obtained from NOAA's Global Data Assimilation System (GDAS). Air quality data, specifically PM 2.5 concentrations, were sourced from local monitoring stations operated by Medan's Environmental Protection Agency. These datasets were complemented by geographic information system (GIS) data to represent pollution patterns spatially.

2.5 Model Configuration

The HYSPLIT model simulated both forward and backward trajectories. The forward trajectory analysis projected pollutant dispersion from known emission sources, while the backward trajectory analysis traced the origins of pollutants observed at specific receptor locations. The model's grid resolution was set to balance computational efficiency and spatial detail. Simulation parameters included Trajectory Height: 100 m, 50 m, and 5 m above ground level (AGL) to capture vertical pollutant distribution. Simulation Time Frame: 120 hours (5 days) to encompass local and regional pollutant transport. Meteorological Inputs: Hourly wind fields, temperature gradients, and atmospheric turbulence data.

2.6 Analytical Approach

The study applied a dual analytical approach to interpret HYSPLIT outputs: Spatial Analysis: Visualization of trajectory paths using GIS tools to identify regions contributing to pollution in Medan. Temporal Analysis: Examination of pollutant transport over time to capture daily and episodic variations in air quality. Trajectory paths were overlaid with industrial zones, transportation corridors, and urban centers to establish correlations between pollutant origins and observed concentrations. Patterns at different altitudes were analyzed to distinguish between local and regional pollution sources.

3. Results and Discussion

3.1 Overview of Air Quality Patterns in Medan

The air quality in Medan during the study period (January–October 2024) showed significant temporal and spatial variations. The analysis highlighted PM 2.5 as the dominant pollutant, with its highest concentration recorded on May 16, 2024. This peak was attributed to local emissions and transboundary pollution influenced by meteorological conditions. The high level of PM 2.5 is a major concern due to its harmful health impacts, as previously emphasized by Babaei et al. (2015). The backward and forward trajectory simulations using the HYSPLIT model provided critical insights into pollutants' transport dynamics, revealing regional and local contributions (Chang et al., 2021; Ellrod, 2015; Stein et al., 2016; Su et al., 2015; Yang et al., 2015).

3.2 Trajectory Analysis: Transport and Dispersion Patterns

The HYSPLIT simulations were conducted at three altitude levels—100 m, 50 m, and 5 m above ground level (AGL)—to analyze pollutant dispersion comprehensively, as seen in **Fig.1** below.

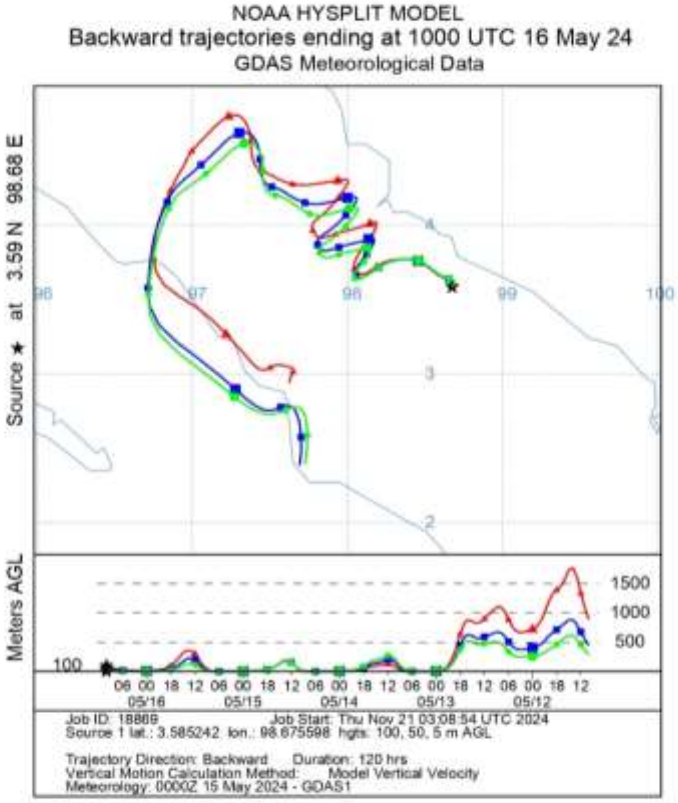

Fig 1: NOAA HYSPLIT result in Medan City
Source: Analysis result, 2024

Figure 1 shows that the trajectories at 100 m AGL represent regional airflows driven by larger-scale meteorological phenomena. The simulation indicated that air masses reaching Medan originated from the southwest, passing over industrial and agricultural regions. This pathway suggests that the high PM 2.5 levels could partially result from biomass burning in neighboring provinces, consistent with findings by several papers (Ilyas, Anggraini, & Rodhiyah, 2022; Nuryanto & Melinda, 2023; Syafaati, 2023; Zahtamal, Restila, Suyanto, & Nazriati, 2023). The relative stability of trajectories at this altitude indicated limited interaction with local surface emissions, highlighting the influence of transboundary pollution.

3.2.1 Mid-Altitude Trajectories (50 m AGL)

At 50 m AGL, the trajectories displayed greater complexity, reflecting the interaction of regional airflows with local meteorological conditions. Urban emissions, including vehicular exhaust and industrial activities, influenced air masses at this altitude. The convergence of these emissions with transboundary pollutants likely amplified PM 2.5 concentrations. This pattern underscores the need for integrated regional and local emission control strategies.

3.2.2 Near-Surface Trajectories (5 m AGL)

The trajectories at 5 m AGL were the most intricate, demonstrating significant interaction with urban activities and geographical features. The dispersion patterns revealed localized hotspots of PM 2.5 concentration, particularly in areas with high traffic density and industrial clusters. The findings align with observations by Tiew et al. (2019), emphasizing the role of human activities in exacerbating near-surface air pollution. Additionally, the looping patterns in some trajectories indicated the presence of atmospheric turbulence, which may have contributed to pollutant stagnation in specific areas.

3.3 Source Contribution Analysis

Backward trajectory analysis was employed to trace the origins of pollutants reaching Medan during the peak pollution event. The results identified two primary sources: Regarding local source activities, including transportation, industrial emissions, and open waste burning, contributed significantly to the PM 2.5 load. Their proximity to population centers underscores their direct impact on public health. As for regional sources, transboundary pollution from biomass burning in neighboring provinces and emissions from industrial zones in other parts of Sumatra were identified as major contributors. These findings highlight the interconnected nature of air pollution across administrative boundaries.

3.4 Temporal Trends and Meteorological Influences

The temporal analysis revealed a strong correlation between pollutant levels and meteorological conditions. Key observations include: (1) Wind direction and speed were crucial in pollutant transport. During the May 16 event, southwesterly winds facilitated the movement of pollutants from biomass-burning regions toward Medan. (2) Higher temperatures and stable atmospheric conditions contributed to pollutant accumulation near the surface, exacerbating air quality issues. (3) Rainfall during certain periods was observed to temporarily reduce PM 2.5 concentrations, reflecting the scavenging effect of precipitation on airborne particulates.

3.5 Comparison with Similar Studies

The findings of this study are consistent with research conducted in other urban settings. For example: (1) Mesjasz-Lech (2019): Reported similar patterns of transboundary pollution contributing to urban air quality degradation in Central Europe. (2) Joshi and Visvanathan (2019): Highlighted the challenges of managing air quality in densely populated urban areas in Asia, emphasizing the role of regional cooperation.

3.6 Recommendations for Air Quality Management

Based on the findings, several recommendations are proposed to address air quality issues in Medan: (1) Strengthen Monitoring Infrastructure: Expand the network of air quality monitoring stations to provide comprehensive spatial coverage and enable real-time data collection. (2) Enhance Emission Control Measures: Implement stricter regulations on industrial emissions and promote the adoption of cleaner technologies. (3) Promote Sustainable Transportation: Encourage public transportation and electric vehicles to reduce traffic-related emissions. (4) Regional Collaboration: Foster cross-border initiatives to address transboundary pollution effectively. (5) Public Awareness (6) Campaigns: Educate communities about the health risks of air pollution and promote behavior changes to minimize emissions.

3.7 Limitations and Future Directions

While this study provides valuable insights, it is subject to certain limitations: (1) Data Availability: Limited access to high-resolution air quality data may affect the accuracy of model outputs. (2) Simplified Assumptions: The HYSPLIT model assumes passive pollutant transport, excluding chemical transformations and interactions. (3) Temporal Scope: The focus on a specific period may not capture long-term trends in air quality. Future research should address these limitations by incorporating chemical modeling, extending the study period, and leveraging satellite-based observations for enhanced spatial coverage.

4. Conclusion

This study analyzed air quality in Medan, focusing on the transport and dispersion of PM 2.5 using the HYSPLIT model, supported by meteorological and local emission data. The findings underscore the intricate interplay between local emissions and transboundary pollution, driven by meteorological conditions, geographical features, and human activities. The results provide valuable insights into pollutant sources and dispersion patterns and their implications for urban air quality management. PM 2.5 concentrations in Medan were influenced by local emissions, such as transportation and industrial activities, and regional pollution, particularly from biomass burning in neighboring provinces. HYSPLIT simulations demonstrated that southwesterly winds transport pollutants into Medan, especially during high pollution events. Trajectory analyses at different altitudes (100 m, 50 m, and 5 m AGL) illustrated distinct pollutant movement dynamics. Local emissions and turbulence dominated near-surface levels, while higher altitudes captured regional transport. Atmospheric stability, wind speed and direction, and rainfall significantly influenced pollutant dispersion and concentration levels. Stable conditions and limited vertical mixing exacerbated air quality issues, particularly in urban hotspots.

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6. References

Callén, M. S., López, J. M., & Mastral, A. M. (2011). Characterization of PM10-bound polycyclic aromatic hydrocarbons in the ambient air of Spanish urban and rural areas. *Journal of Environmental Monitoring, 13*(2), 319-327. doi:10.1039/c0em00425a

Chang, L., Jiang, N., Watt, S., Azzi, M., Riley, M., & Barthelemy, X. (2021). *The Use Of 'Hysplit In Nsw' In Air Quality Management And Forecasting*.

Ellrod, G. (2015). *Use of the NOAA ARL HYSPLIT Trajectory Model For the Short Range Prediction of Coastal Stratus and Fog*.

Ilyas, R. M., Anggraini, F. J., & Rodhiyah, Z. (2022). Pemodelan Sebaran Polutan PM10 dan PM2,5 Model Hysplit pada Kawasan Gentala Arasy Kota Jambi. *Jurnal Engineering, 4*(2), 39-54. Retrieved from https://online-journal.unja.ac.id/JurnalEngineering/article/view/20840

Insian, W., Yabueng, N., Wiriya, W., & Chantara, S. (2022). Size-fractionated PM-bound PAHs in urban and rural atmospheres of northern Thailand for respiratory health risk assessment. *Environmental Pollution, 293*, 118488. doi:https://doi.org/10.1016/j.envpol.2021.118488

Jakovljević, I., Pehnec, G., Vađić, V., Čačković, M., Tomašić, V., & Jelinić, J. D. (2018). Polycyclic aromatic hydrocarbons in PM10, PM2.5 and PM1 particle fractions in an urban area. *Air Quality, Atmosphere & Health, 11*(7), 843-854. doi:10.1007/s11869-018-0603-3

Jamhari, A. A., Latif, M. T., Wahab, M. I. A., Othman, M., Hamid, H. H. A., Tekasakul, P., . . . Rajab, N. F. (2021). Size-segregated atmospheric polycyclic aromatic hydrocarbons down to PM0.1 in urban tropical environment: Temporal distribution, potential sources and human health risk. *Urban Climate, 40*, 100996. doi:https://doi.org/10.1016/j.uclim.2021.100996

Marlier, M., Defries, R., Kim, P., Gaveau, D., Koplitz, S., Jacob, D., . . . Myers, S. (2015). Regional air quality impacts of future fire emissions in Sumatra and Kalimantan. *Environmental Research Letters, 10*. doi:10.1088/1748-9326/10/5/054010

Mohanraj, R., Solaraj, G., & Dhanakumar, S. (2011). PM 2.5 and PAH Concentrations in Urban Atmosphere of Tiruchirappalli, India. *Bulletin of Environmental Contamination and Toxicology, 87*(3), 330-335. doi:10.1007/s00128-011-0349-1

Nisa'ul Khoir, A., M.Cc, S., Ahmad, M., & Nurhayati, H. (2020). Analysis of PM 10 in urban and rural environment in Sumatra Island over the past half-decade. *IOP Conference Series: Earth and Environmental Science, 489*, 012001. doi:10.1088/1755-1315/489/1/012001

Nuryanto, N., & Melinda, S. (2023). Identifikasi Sumber Particulate Matter (PM) 2.5 di Sorong Berdasarkan READY Hysplit Backward Trajectory. *Buletin GAW Bariri, 4*, 11-20. doi:10.31172/bgb.v4i1.80

Siudek, P. (2022). Seasonal distribution of PM2.5-bound polycyclic aromatic hydrocarbons as a critical indicator of air quality and health impact in a coastal-urban region of Poland. *Science of The Total Environment, 827*, 154375. doi:https://doi.org/10.1016/j.scitotenv.2022.154375

Stein, A., Draxler, R. R., Rolph, G., Stunder, B., Cohen, M., & Ngan, F. (2016). NOAA's HYSPLIT atmospheric transport and dispersion modeling system. *Bulletin of the American Meteorological Society, 96*, 150504130527006. doi:10.1175/BAMS-D-14-00110.1

Su, L., Yuan, Z., Fung, J., & Lau, A. (2015). A comparison of HYSPLIT backward trajectories generated from two GDAS datasets. *The Science of the total environment, 506-507*, 527-537. doi:10.1016/j.scitotenv.2014.11.072

Syafaati, A. D. (2023). Analysis Of Air Quality Pm2.5 Parameter In Sorong City Area Based On ISPU. *Megasains, 14*(2). doi:https://doi.org/10.46824/megasains.v14i2.131

Yang, S., Kalpakis, K., & Yesha, Y. (2015). *Improving HYSPLIT Particle Dispersion Prediction with Data Assimilation*.

Zahtamal, Z., Restila, R., Suyanto, S., & Nazriati, E. (2023). Korelasi Sebaran Titik Panas Dengan Kualitas Udara Di Kota Pekanbaru. *Prepotif : Jurnal Kesehatan Masyarakat, 7*(1), 283 - 291. doi:10.31004/prepotif.v7i1.6888