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Original Article

# Evaluating Industrial Stack Emissions in Dong Thap Province, Vietnam Using AERMOD Model

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**Abstract:** This study employs the AERMOD dispersion model to analyze the spatial and temporal distribution of total suspended particles (TSP), sulfur dioxide ($SO_2$), and nitrogen dioxide ($NO_2$) from 36 industrial stacks across 19 major plants in Dong Thap province, Vietnam. Using high-resolution meteorological data from 2021-2023 from ERA5 reanalysis dataset, the research examines maximum concentrations, 99$^{th}$ percentile scenarios, and annual averages. Results indicate that while extreme events can produce localized pollutant concentrations exceeding national standards—with maximum 1-h concentrations reaching 312 µg/m³ for TSP, 373.2 µg/m³ for $SO_2$, and 643.4 µg/m³ for $NO_2$—these occurrences are infrequent. The 99$^{th}$ percentile 1-h concentrations (68.8 µg/m³ TSP, 58.8 µg/m³ $SO_2$, 101 µg/m³ $NO_2$) and annual averages remain below regulatory limits, suggesting severe pollution events occur less than 1% of the time. Spatial analysis reveals higher pollutant concentrations in southern Dong Thap, particularly Sa Dec and Cao Lanh cities, with rapid dispersion facilitated by the flat terrain. Seasonal variations in pollutant concentrations are evident, with higher levels observed during the dry season compared to the wet season. The study shows the significant influence of seasonal monsoon patterns on pollutant dispersion, with the southwest monsoon (May-October) associated with higher wind speeds and broader pollutant dispersion. This research provides crucial insights for air quality management in rapidly industrializing regions, highlighting the need for targeted mitigation strategies in industrial zones while considering the potential for inter-provincial pollution transport.

*Keywords:* AERMOD, Dong Thap, air pollution, stack emission, modeling.

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## 1. Introduction

The Mekong Delta faces growing environmental challenges as industry transforms its landscape. Dong Thap province is at the center of this change, where industrial stacks are major sources of air pollution, including total suspended particles (TSP), sulfur dioxide ($SO_2$), and nitrogen dioxide ($NO_2$). The number of industrial parks in Dong Thap has grown from just one in 1998 to four in 2024, with plans for an additional five by 2030. As Dong Thap develops, its traditional farming focus is giving way to more factories. This growth has led to more industrial stack emissions, worsening air quality. These pollutants affect not just Dong Thap but the whole Mekong Delta and may even change regional economic patterns [1].

Recent studies show that industrial emissions are a big part of air pollution in developing Southeast Asian regions [2-4]. In Vietnam, areas with rapid industrial growth are seeing this problem grow [5]. Similar issues in nearby countries like Thailand show this is a regional concern [6]. The Mekong Delta's unique geography and weather make these emissions even more impactful, calling for tailored solutions in Dong Thap [7, 8]. The health effects of industrial stack emissions are serious and widespread. These pollutants can harm breathing and heart health [9]. Studies in Asia have linked exposure to industrial air pollution with more breathing problems, heart issues, and early deaths [10, 11]. The economic cost is huge, with yearly expenses in the billions due to healthcare needs and lost work time [12].

Climate change worsens the problem of industrial emissions in Dong Thap, particularly as projections indicate that its effects will be more severe in Vietnam, especially in the southern regions [13-15]. The resulting changes in climate lead to increased extreme weather events, which can influence how pollutants disperse and concentrate in the area. Consequently, this may heighten the adverse effects of emissions on local communities. This mix of industrial emissions and changing climate adds complexity to managing air quality in the area [16-18]. Currently, air quality monitoring in Dong Thap is insufficient to manage the growing emissions from industrial stacks. With limited monitoring stations and infrequent testing, the system fails to adequately track the evolving nature of industrial pollution. This lack of comprehensive monitoring creates challenges in designing effective pollution control measures and leaves local communities exposed to potential air quality risks [19, 20]. Without reliable data, the development of targeted pollution reduction strategies is hindered, further increasing the vulnerability of sensitive populations, such as children and the elderly, who are more susceptible to air pollution-related health issues [21].

This study aims to address critical knowledge gaps by using advanced modeling and local weather data to assess industrial stack emissions in Dong Thap, focusing on their contributions to TSP, $SO_2$, and $NO_2$ levels, and mapping the spatial and temporal distribution of these pollutants across the province. The results of this study will help inform policy-making in Dong Thap and the wider Mekong Delta region. By explaining the patterns and impacts of industrial TSP, $SO_2$, and $NO_2$ emissions, we aim to give local authorities, industry stakeholders, and communities the knowledge they need to balance industrial growth with better air quality.

## 2. Data and Methods

### *2.1. Study Area*

Dong Thap province covers an area of approximately 3,377 $km^2$. The province is divided into 12 administrative units, including 3 cities (Sa Dec, Cao Lanh, and Hong Ngu) and 9 districts (Figure 1). Characterized by its low-lying topography, Dong Thap's landscape is dominated by flat plains with an average elevation of 1-2 m above sea level, interspersed with a network of rivers and canals. The province experiences a tropical monsoon climate with two distinct seasons: a rainy season from

May to November and a dry season from December to April. Annual rainfall averages around 1,500 mm, with temperatures ranging from 24 to 32 °C throughout the year. Historically an agricultural powerhouse, Dong Thap has seen a significant shift towards industrialization in recent years. From 2015 to 2023, the number of industrial enterprises in the province increased by 45%, with the industrial sector's contribution to the provincial GDP rising from 28 to 36%. This rapid industrial growth has been particularly pronounced in the food processing, textile, and construction materials sectors, leading to a corresponding increase in the number of industrial stacks and associated emissions.

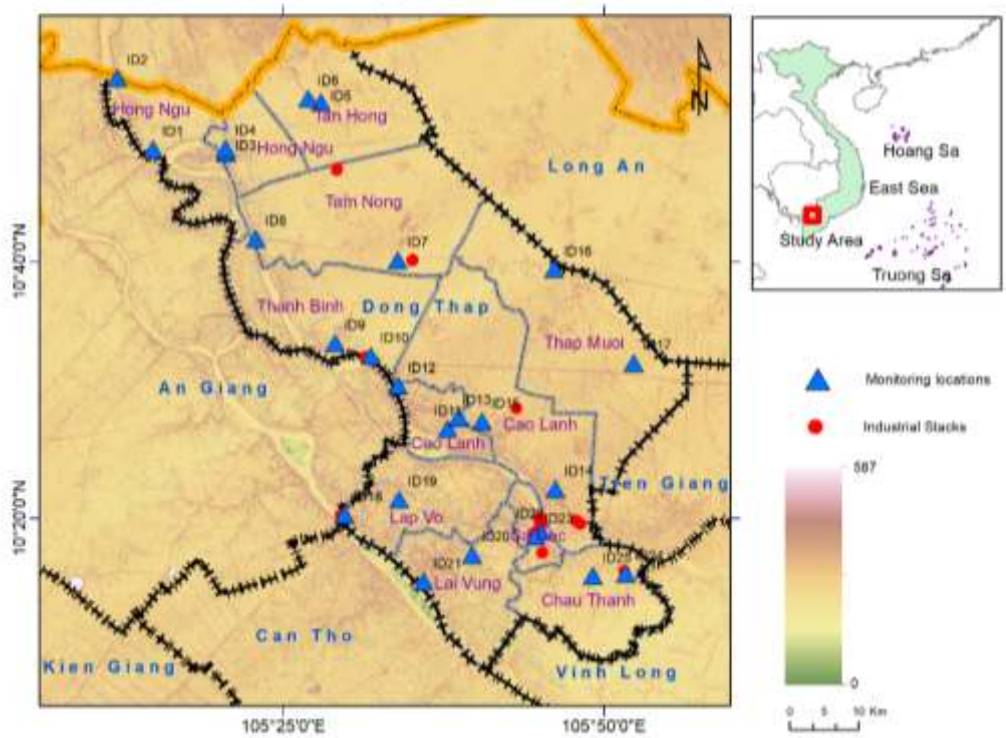


Figure 1. Administrative map of Dong Thap Province overlaid on an Shuttle Radar Topography Mission (SRTM) terrain map, with red dots marking the locations of the 19 key industrial plants and their 36 emision stacks analyzed in this study. Location of air quality stations is indicated in blue triangles.

### *2.2. Dispersion Model for Stack Emission*

For this study, we employ the American Meteorological Society/Environmental Protection Agency Regulatory Model (AERMOD) [22] to simulate the dispersion of TSP, $SO_2$, and $NO_2$ from industrial stacks in Dong Thap province. AERMOD is a state-of-the-art steady-state plume model designed for short-range dispersion of air pollutant emissions from stationary industrial sources [23-25]. The AERMOD model has become a widely used tool for air quality assessment in Vietnam, particularly for evaluating industrial projects, urban planning, and regulatory compliance. It has been applied in various regions, including thermal power plant assessments in Binh Thuan [26], Cam Pha city [27], transportation exhaust emission in Hanoi [28], cement factory emissions in Quang Ninh [29], and industrial zones in Ho Chi Minh City [30]. Its versatility in handling Vietnam's diverse conditions has made it a standard in environmental impact assessments, as recommended by the Vietnam

Ministry of Natural Resources and Environment [31]. This extensive use provides a strong foundation for its application in Dong Thap, ensuring consistent methodology and comparable results.

*2.3. Emission Source Characterization*

Our study focuses on 19 major industrial plants in Dong Thap province, identified as significant contributors to air pollution, as suggested by the Department of Natural Resources and Environment of Dong Thap province. These plants, representing diverse sectors such as food processing, construction materials manufacturing, chemical production, animal feed production, and aquaculture, operate a total of 36 industrial stacks distributed across various industrial zones and clusters throughout the province (Figure 1). Table 1 provides essential details for each chimney, including coordinates, stack height, diameter, flow rate and emission rate. Emission calculations for TSP, $SO_2$ and $NO_2$ were relied on data from automatic air monitoring systems installed on these stacks, as mandated by state regulations. The data, collected during 2021 and 2022, offers a solid foundation for our analysis by providing accurate real-time measurements of emissions from these industrial sources. In addition to this monitoring data, we incorporated supplementary information from Environmental Impact Assessment (EIA) reports, which include essential details about chimney characteristics such as height, diameter, exit gas velocity, and temperature, as well as the specific industrial processes involved.

*2.4. Air Quality Data*

The ambient air quality monitoring data for Dong Thap Province were collected from 25 designated monitoring sites, as mandated by the Dong Thap Provincial People's Committee. The coordinates and specific locations of these sites are presented in Figure 1 and Table 2. The air quality data were collected and analyzed under the organization and supervision of the Dong Thap Department of Natural Resources and Environment and certified laboratories, following standard procedures outlined in QCVN 05:2013/BTNMT. The monitored pollutants include TSP, $NO_2$, and $SO_2$, with data recorded at hourly intervals. This study analyzed air quality data from two monitoring campaigns conducted in 2022 to capture seasonal variations: rainy season (September 19–22, 2022) and dry season (March 28–31, 2022). These datasets were further utilized for AERMOD model validation, ensuring accurate representation of air pollution dispersion across different meteorological conditions.

*2.5. Meteorological, Geographical and Land Cover Data*

Our study used ERA5 reanalysis data from the ECMWF for January 2021 to December 2023, including high-resolution hourly data on wind, cloud cover, radiation, temperature, precipitation, and atmospheric pressure. Upper air observations from the Can Tho radiosonde station were added for planetary boundary layer calculations. The modeling covered 1,095 days and produced 26,280 hourly simulations, capturing diurnal, seasonal, and inter-annual pollutant dispersion variations. The meteorological data was processed using AERMET, a sub-program of AERMOD, to ensure accurate TSP dispersion modeling.

High-resolution terrain data from the Shuttle Radar Topography Mission (SRTM) at 30-m resolution were processed and resampled to fit the 200 m grid. A combined method was used for land use classification, integrating the Global Land Cover dataset (100 m resolution) with satellite imagery from Google Maps. This data was refined using the AERMET View Land User Creator tool, producing a 30-m resolution land use map (Figure 2). The final output included a 12-sector scheme representing key surface parameters such as surface roughness, Bowen ratio, and albedo, essential for the meteorological input in the AERMOD model.

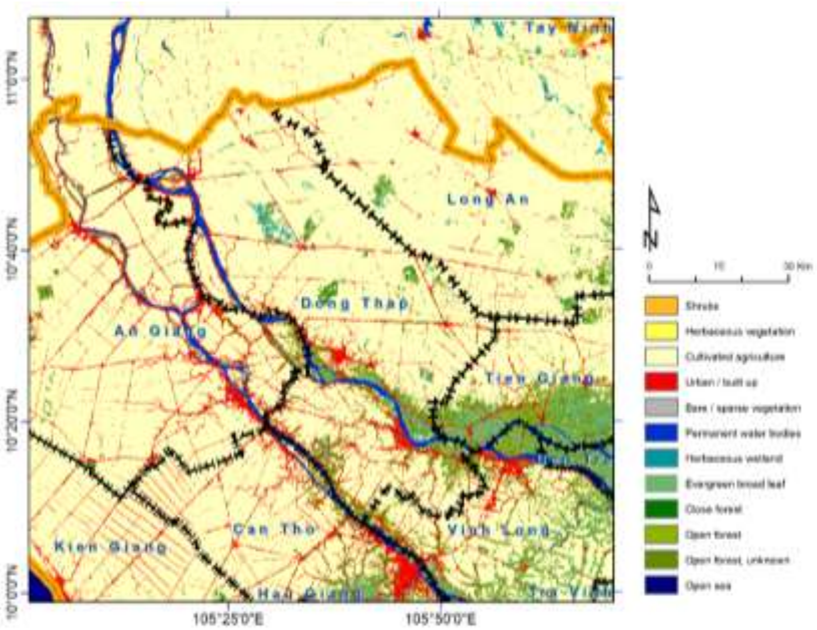


Figure 2. Land cover map of the study area.

Table 1. Coordinates, locations, and number of emission stacks for each of the 19 key industrial plants in Dong Thap provinSTT

| | Company | Stack type | Location (UTM) | | Height (m) | Diameter (mm) | Volume ($m^3$/h) | Emission rate (g/s) | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | Lat | Long | | | | TSP | $SO_2$ | $NO_2$ |
| 1 | Bich Chi Food Joint Stock Company | Boiler 10 ton/h | 1137484 | 582484.5 | 18 | 750 | 18.432 | 0.712 | 0.013 | 0.208 |
| | | Boiler 18 ton/h | 1137484 | 582484.5 | 24 | 1.700 | 12.586 | 0.493 | 0.009 | 0.180 |
| 2 | Hung Ca 9 Joint Stock Company | Boiler 8 ton/h | 1165326 | 557981.3 | 22 | 950 | 155.916 | 5.111 | 0.113 | 1.005 |
| | | Boiler 8 ton/h | 1165326 | 557981.3 | 22 | 950 | 155.916 | 3.681 | 0.113 | 6.284 |
| 3 | Vinh Hoan Joint Stock Company | Boiler 18 ton/h | 1165272 | 558271 | 20 | 1.000 | 27.982 | 1.150 | 0.020 | 1.501 |
| 4 | Pilmico VHF Joint Stock Company | Boiler 18 ton/h | 1165694 | 557368.2 | 18 | 1.200 | 30.000 | 1.275 | 0.022 | 1.258 |
| | | Boiler 12 ton/h | 1165694 | 557368.2 | 18 | 1.000 | 20.000 | 0.939 | 0.015 | 0.954 |
| 5 | Emivest Feedmill (TG) Vietnam Co., Ltd - Dong Thap Branch | Boiler 19 ton/h | 1142103 | 582251.4 | 21,2 | 1.000 | 60.000 | 2.700 | 0.044 | 2.720 |
| 6 | Mekong Aquatic Feed Co., Ltd | Boiler 15 ton/h | 1179557 | 563998.1 | 24 | 1.200 | 30.000 | 0.933 | 0.542 | 0.567 |
| | | Boiler 8 tons/h | 1179606 | 563897.8 | 24 | 750 | 30.000 | 0.933 | 0.500 | 0.558 |
| | | Boiler 20 ton/h | 1179606 | 563897.8 | 21 | 1.200 | 33.691 | 0.947 | 0.608 | 0.636 |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| 7 | Tourism and Aquatic Development Investment Joint Stock Company | Boiler 15 ton/h | 1142981 | 554171.2 | 25 | 1.100 | 21.857 | 1.008 | 0.016 | 0.023 |
| | | Boiler 15 ton/h | 1142985 | 554074.5 | 25 | 1.100 | 21.857 | 0.528 | 0.016 | 0.038 |
| | | Boiler 12 ton/h | 1142981 | 554009.9 | 21 | 900 | 17.485 | 0.850 | 0.013 | 0.017 |
| 8 | International Development Investment Joint Stock Company - I.D.I | Boiler 12 ton/h | 1142740 | 553876.3 | 18 | 820 | 66.338 | 1.787 | 0.719 | 5.270 |
| | | Boiler 12 ton/h | 1142740 | 553874.2 | 18 | 820 | 66.338 | 1.787 | 0.719 | 5.270 |
| | | Boiler 12 ton/h | 1142748 | 553893.6 | 18 | 820 | 66.338 | 1.787 | 0.719 | 5.270 |
| 9 | Tien Phat Environmental Service Trading Production Co., Ltd. | Boiler 1 ton/h | 1158197 | 578661.4 | 25,5 | 1.000 | 7.000 | 12.129 | 0.212 | 0.791 |
| 10 | Cargill Vietnam Co., Ltd - Dong Thap Branch | Boiler 3 ton/h | 1141757 | 582407.4 | 10 | 300 | 40.000 | 1.000 | 2.389 | 1.767 |
| | | Boiler 6 ton/h | 1141757 | 582407.4 | 10 | 300 | 69.696 | 2.730 | 3.833 | 9.893 |
| 11 | NewHope Aquatic Feed Co., Ltd - Dong Thap | Boiler 10 ton/h | 1141768 | 582203.5 | 17 | 1.000 | 28.116 | 1.195 | 1.687 | 2.468 |
| 12 | Feed One Aquatic Feed Co., Ltd | Boiler 9 ton/h | 1142073 | 587340.6 | 20 | 820 | 10.000 | 0.210 | 0.411 | 0.311 |
| | | Boiler 9 ton/h | 1142073 | 587340.6 | 20 | 820 | 10.000 | 0.210 | 0.411 | 0.311 |
| 13 | USFEED Co., Ltd | Boiler 9 ton/h | 1140222 | 581289.6 | 15 | 750 | 10.000 | 0.144 | 0.015 | 0.567 |
| 14 | Viet Thang Livestock Feed Joint Stock Company | Boiler 18 ton/h | 1141497 | 582308.1 | 20 | 1.000 | 30.000 | 1.392 | 0.022 | 0.017 |
| | | Boiler 18 ton/h | 1141512 | 582280.2 | 20 | 1.000 | 30.000 | 1.492 | 0.022 | 0.017 |
| 15 | Ha Thanh Ceramic Tile Factory | Spray dryer exhaust | 1192622 | 553228.1 | 20 | 750 | 7.618 | 0.178 | 0.047 | 0.078 |
| | | Raw brick filn | 1192622 | 553228.1 | 20 | 750 | 8.394 | 0.266 | 0.333 | 0.201 |
| | | Glaze kiln | 1192578 | 553193.9 | 20 | 750 | 5.420 | 0.182 | 0.229 | 0.146 |
| 16 | Guyomarch Co., Ltd | Boiler 9 ton/h | 1134894 | 594181.4 | 20 | 1.000 | 3.315 | 0.053 | 0.044 | 0.125 |
| 17 | Cuu Long Seafood Import-Export Joint Stock Company | Boiler 6 ton/h | 1142483 | 582140.5 | 22 | 750 | 9.000 | 0.358 | 0.095 | 0.013 |
| | | Boiler 15 ton/h | 1142483 | 582140.5 | 24 | 1.150 | 40.000 | 1.444 | 0.378 | 0.389 |
| | | Boiler 15 ton/h | 1142483 | 582140.5 | 24 | 900 | 40.000 | 1.411 | 0.911 | 0.022 |
| 18 | Co May Lai Vung Co., Ltd | Boiler 15 ton/h | 1132848 | 565632.3 | 20 | 1.000 | 14.799 | 0.370 | 0.011 | 0.150 |
| 19 | Phat Tien 3 Livestock Feed Joint Stock Company | Boiler 9 ton/h | 1141686 | 587900.8 | 20 | 1.100 | 10.000 | 0.210 | 0.411 | 0.311 |
| | | Boiler 9 ton/h | 1141686 | 587900.8 | 24 | 1.050 | 10.000 | 0.210 | 0.411 | 0.311 |

Table 2. Coordinates and locations of air quality monitoring stations

| No. | Location | Label | Location (UTM) | |
|---|---|---|---|---|
| | | | Lat | Long |
| 1 | Roundabout on DT 841 Road, Thuong Thoi Tien Town. | ID1 | 1195453 | 526829 |
| 2 | DT 841 Road, in front of Thuong Phuoc 1 Market. | ID2 | 1205702 | 521748 |
| 3 | National Road 30, in front of Hong Ngu Market. | ID3 | 1194911 | 537173 |
| 4 | Intersection of National Road 30 and Dinh Tien Hoang Road. | ID4 | 1195589 | 537173 |
| 5 | Nguyen Hue Road, in front of the People's Committee of Tan Hong District, Sa Rai Town. | ID5 | 1202236 | 550699 |
| 6 | Roundabout at National Road 30 and Huynh Cong Tri Road, Sa Rai Town. | ID6 | 1202758 | 548887 |
| 7 | Intersection of DT 844 Road and Nguyen Van Troi Road, Tram Chim Town. | ID7 | 1179580 | 561650 |
| 8 | Intersection of National Road 30 and DT 844 Road, An Long Commune. | ID8 | 1182603 | 541480 |
| 9 | National Road 30, in front of the People's Committee of Thanh Binh Town. | ID9 | 1167619 | 552735 |
| 10 | National Road 30, in front of Binh Thanh Industrial Cluster, Binh Thanh Commune. | ID10 | 1165774 | 557852 |
| 11 | Nguyen Sinh Sacs Monument, Pham Huu Lau Road, Ward 4. | ID11 | 1155294 | 568822 |
| 12 | Entrance to Tran Quoc Toan Industrial Park, National Road 30, Ward 11. | ID12 | 1161459 | 561758 |
| 13 | Roundabout at Dong Thap Martyrs Cemetery, My Phu Ward. | ID13 | 1156932 | 570320 |
| 14 | National Road 30, entrance to My Hiep Industrial Cluster, My Hiep Commune. | ID14 | 1146669 | 584128 |
| 15 | Intersection at Ong Bau, My Tho Town. | ID15 | 1156385 | 573681 |
| 16 | Entrance to Truong Xuan Industrial Cluster, Truong Xuan Commune. | ID16 | 1178320 | 583889 |
| 17 | Entrance to Tan Kieu Industrial Cluster, Tan Kieu Commune. | ID17 | 1164862 | 595230 |
| 18 | National Road 80, entrance to Vam Cong Industrial Cluster, Binh Thanh Commune. | ID18 | 1142967 | 554154 |
| 19 | Bac Song Xang Industrial Cluster Area, Binh Thanh Trung. | ID19 | 1145160 | 561898 |
| 20 | National Road 80, in front of Lai Vung District People's Committee, Lai Vung Town. | ID20 | 1137250 | 572289 |
| 21 | National Road 54, entrance to Song Hau Industrial Park, Tan Thanh Commune. | ID21 | 1133331 | 565439 |
| 22 | Intersection at C Roundabout, Sa Dec Industrial Park, Tan Khanh Dong Commune. | ID22 | 1140566 | 582081 |
| 23 | Intersection of DT 848 Road and Nguyen Chi Thanh Road, near Area A, Sa Dec Industrial Park, An Hoa Ward. | ID23 | 1139860 | 581327 |
| 24 | Entrance to Cai Tau Ha - An Nhon Industrial Cluster, National Road 80, An Nhon Commune. | ID24 | 1134541 | 594199 |
| 25 | Entrance to Tan Lap Industrial Cluster, Tan Nhuan Dong Commune. | ID25 | 1134257 | 589552 |

*2.6. Simulation configuration*

The modeling area, focused on Dong Thap Province, spans 100 km by 100 km and is structured into a Cartesian grid of 500 x 500 cells, each measuring 200 m. This study investigates the dispersion patterns of TSP, $SO_2$, and $NO_2$ emissions from industrial smokestacks through three distinct experimental approaches. Firstly, the study identifies peak concentrations of each pollutant by examining the maximum recorded values at every grid point from hourly simulations throughout the researching period, which capture the most significant pollution events. Secondly, it analyzes the 99th percentile scenario, which targets infrequent yet critical spikes in pollutant levels, reveal the effect on extreme pollution risks. Lastly, the analysis evaluates the annual average concentrations of TSP, $SO_2$, and $NO_2$ for the years 2021 to 2023 to discern seasonal cycle trends. These scenarios are modeled independently from other pollution sources to ensure that the findings accurately represent emissions from industrial activities alone.

## 3. Results and Discussion

### *3.1. Assessment of ERA5 Meteorological Data*

The ERA5 dataset was validated against measurements from the Can Tho station (10.033°N, 105.767°E), which is the nearest national meteorological station for wind data. While the station records wind in eight directional quadrants every 6 h, ERA5 provides hourly data in degrees. Both datasets were aggregated to daily averages and eight directional sectors for comparison. Wind roses from both datasets for 2021-2023 show similar prevailing wind directions and speed distributions (Figure 3). Low to moderate winds dominate in both datasets, though station observations record higher frequencies of strong winds than ERA5. The radial frequencies follow consistent patterns, with minor differences likely due to local effects captured by station measurements but smoothed in ERA5's grid-based data. The analysis confirms ERA5 reliably represents regional wind patterns while tending to underestimate peak wind speeds.

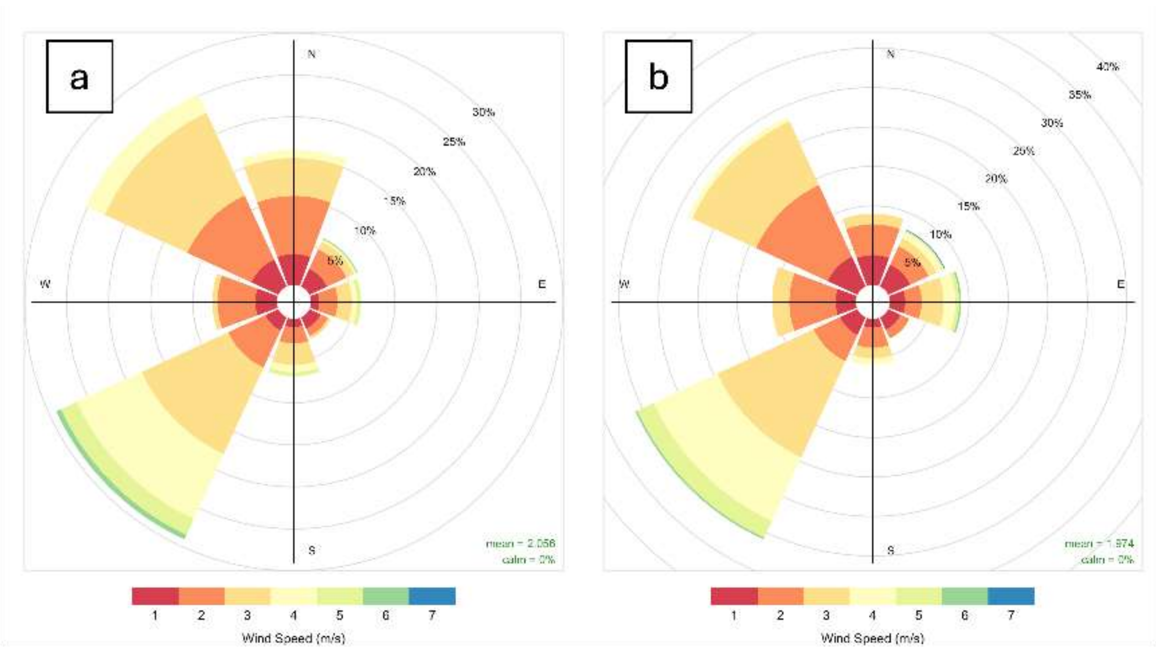


Figure 3. Windrose comparison between (a) station data and (b) ERA5 data for 2021-2023 at Can Tho station

Figure 4 presents a detailed comparison of wind speed and temperature between measured data and ERA5 reanalysis. For wind speed, ERA5 shows good agreement with observations, achieving a correlation coefficient of 0.87 and RMSE of 0.57 m/s. However, the analysis reveals increased scatter at lower wind speeds (0-2 m/s), and the regression line's deviation from the 1:1 reference line indicates systematic biases in ERA5 estimates. Surface temperature comparisons shows excellent agreement between ERA5 and measurements. Data points closely follow the 1:1 reference line across the temperature range of 24-32 °C, indicating high reliability of ERA5 temperature estimates. Overall, ERA5 reanalysis data provide a reliable representation of both wind speed and surface temperature, the key variables influencing air pollutant dispersion, indicating its suitability for use in Dong Thap with acceptable accuracy.

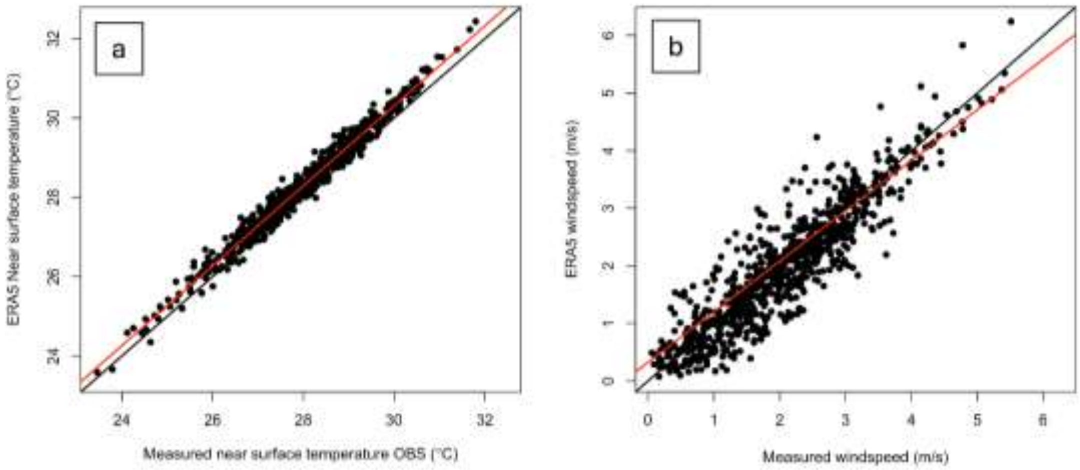


Figure 4. Comparison of measured data and ERA5 data for (a) surface temperature and (b) windspeed at Can Tho Station for 2021-2023. The black line represents the 1:1 line, and the red line shows the regression between measured and ERA5 data.

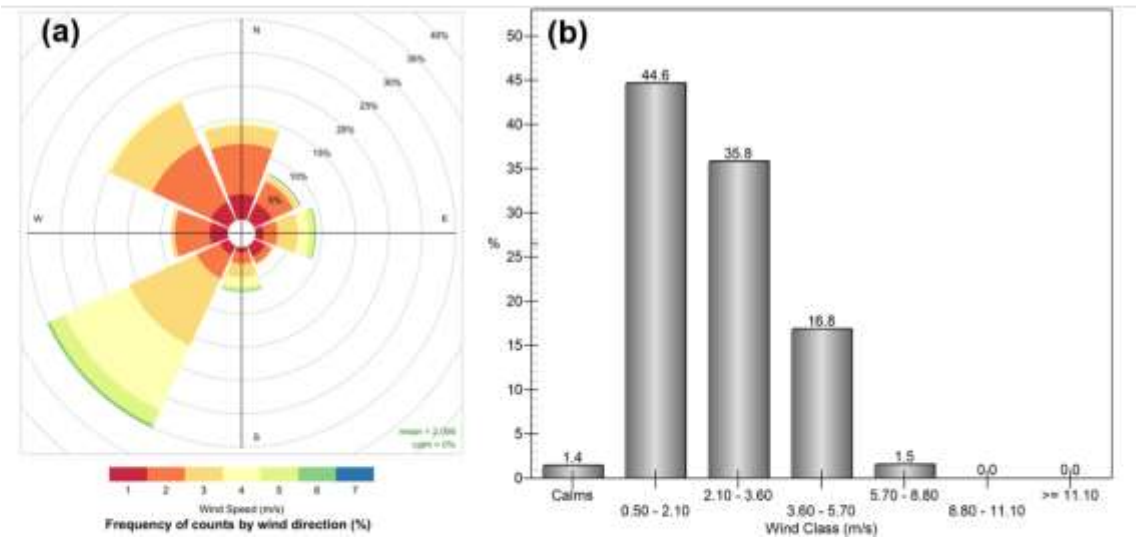


Figure 5. (a) Windrose and (b) wind speed distribution at Dong Thap province during 2021-2023 by ERA5 reanalysis dataset.

### *3.2. Prevailing Wind Patterns in Dong Thap Province*

The wind patterns in Dong Thap province, located in the Mekong Delta, show distinct seasonal variations influenced by the Southeast Asian monsoon system. Data from 2021 to 2023 highlight these prevailing wind patterns (Figure 5). The primary wind direction is from the west-northwest (WNW) to southwest (SW), reflecting broader regional trends seen in the lower Mekong Basin. Wind speeds generally range between 0.5 and 5.7 m/s, with most winds falling in the lower range of 0.5 to 3.6 m/s. Specifically, 44.6% of winds occur in the 0.5-2.1 m/s range, while 35.8% are within the 2.1-3.6 m/s range. Winds in the 3.6-5.7 m/s range account for 16.8%, and only 1.5% exceed 5.7 m/s. Calm conditions, with very low wind speeds, occur just 2.07% of the time, indicating the region's predominantly mild winds.

Seasonal wind patterns in the region are strongly influenced by the monsoon system. During the southwest monsoon (May to October), winds predominantly originate from the west and southwest, carrying warm, moist air from the Indian Ocean and Gulf of Thailand, which drives the rainy season. Higher wind speeds (2.1–5.7 m/s) during this period result from the pressure gradient between the Tibetan Plateau low and the Mascarene high in the southern Indian Ocean [32, 33]. In contrast, the northeast monsoon (November to April) brings cooler, drier air from the Siberian high-pressure system, creating the dry season. Winds during this period shift to the northeast, with lower speeds (0.5–2.1 m/s) [34]. Transition periods in April–May and October–November feature variable wind directions and speeds as dominant weather systems shift [35].

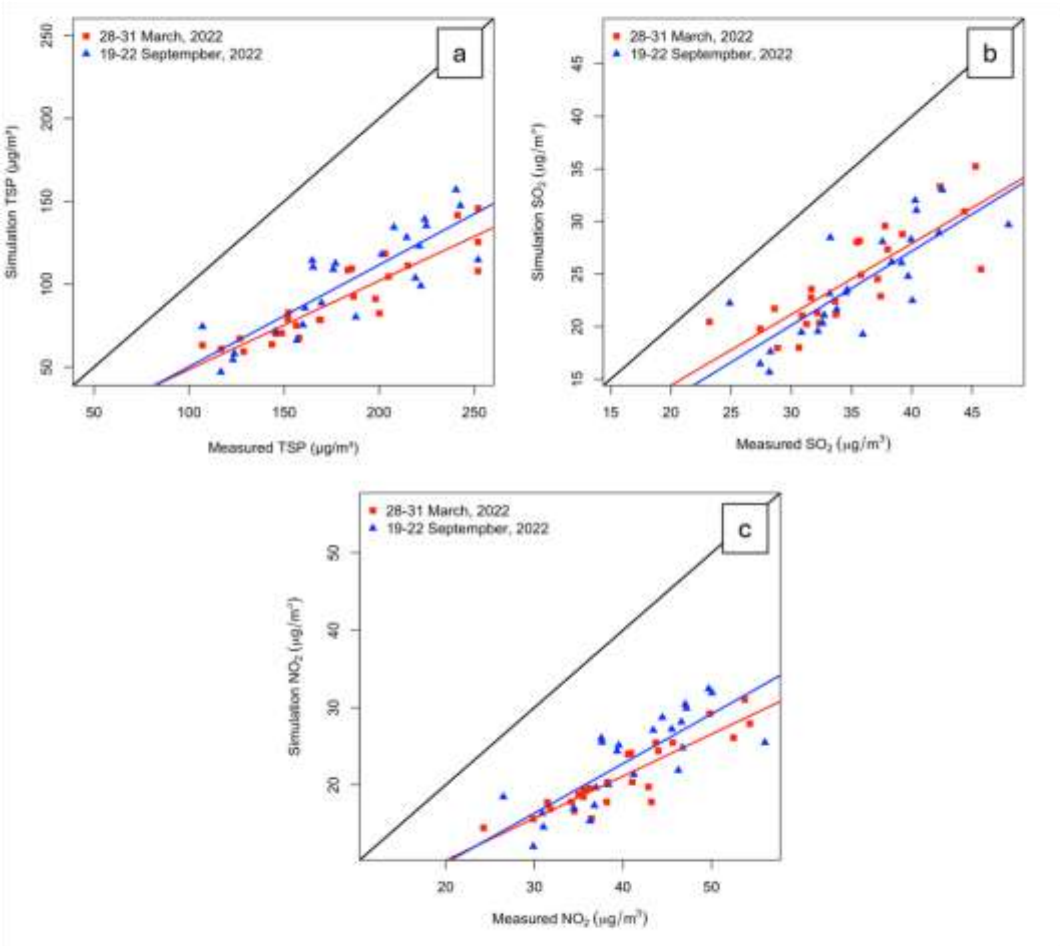


Figure 6. Comparison of measured air quality data and AERMOD results for (a) TSP, (b) $SO_2$ and (c) $NO_2$. The black line represents the 1:1 line. The red and blue lines show the regression between measured data and AERMOD results for March 28-31, 2022, and September 19-22, 2022, respectively.

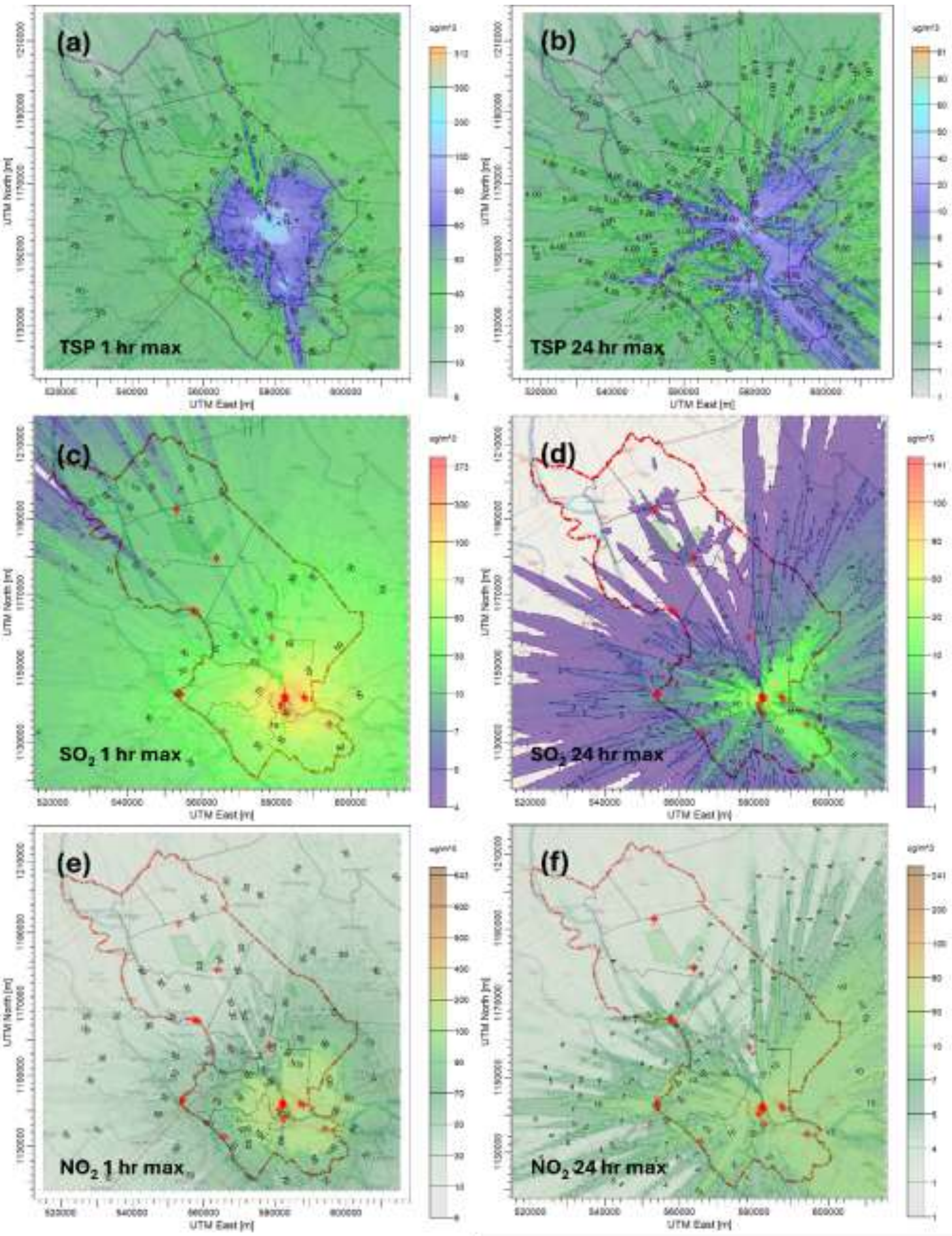


Figure 7. Maximum stack emissions dispersion events from transportation sources: (a) maximum 1-h TSP, (b) maximum 24-h TSP, (c) maximum 1-h $SO_2$, (d) maximum 24-h $SO_2$, (e) maximum 1-h $NO_2$, and (f) maximum 24-h $NO_2$.

### *3.3. Comparative Analysis of Measured and Modeled Air Quality Data*

The comparison between measured air quality data and AERMOD model predictions for TSP, $SO_2$, and $NO_2$ in Dong Thap Province during March 28–31 and September 19–22, 2022, reveals that industrial stack emissions account for only 30–70% of total pollution (Figure 6). The systematic underestimation across all pollutants, as evidenced by regression lines consistently falling below the 1:1 reference line, originates from AERMOD's focus on industrial stack emissions, excluding contributions from other significant sources such as vehicles, agriculture, natural phenomena, and household activities. Among the pollutants, TSP exhibits the largest deviations and the widest data scatter, highlighting the diverse atmospheric sources beyond industrial emissions, including road dust, construction activities, and biomass burning. All three pollutants show greater deviations at higher concentrations, suggesting that extreme pollution events likely involve multiple unaccounted sources beyond industrial stacks. The consistent model performance between March (dry season) and September (rainy season) further indicates that the observed limitations are structural rather than seasonal, underscoring the need to expand the model to include a wider range of emission sources for more accurate predictions.

### *3.4. Extreme Concentration and Dispersion of Stack Emissions from Major Industries*

The analysis of pollutant dispersion from industrial stacks in Dong Thap province reveals that air quality impacts from TSP, $SO_2$, and $NO_2$ are generally within acceptable limits (Figure 7). Maximum 1-h TSP concentrations reach 312 µg/m³, slightly higher than the national standard of 300 µg/m³, indicating industrial emissions can have direct adverse effects on the air quality. Sa Dec and Cao Lanh cities experience the highest concentrations, with TSP levels at the industrial central ranging from 200 to 300 µg/m³ in central areas. However, these elevated concentrations are localized, typically decreasing to below 200 µg/m³ within 2 km downwind of factories under average maximum hourly emissions. Pollution is concentrated primarily near the industrial stacks due to the cumulative impact of multiple emission sources. Dong Thap's flat terrain facilitates rapid pollutant dispersion, reducing localized pollution events but potentially affecting neighboring provinces like Vinh Long and Can Tho, which located downwind. The southern part of Dong Thap, where over half of the studied factories are located, shows more pronounced air quality impacts. In contrast, Hong Ngu city in the north of Dong Thap, with only one industrial facility, experiences minimal TSP impacts, averaging below 20 µg/m³ even during peak emissions. The 24-h maximum TSP concentrations in Dong Thap province exhibit a more dispersed pattern compared to the 1-h maximum, with values significantly lower due to averaging over a longer period. Near pollutant sources, 24-h maximum TSP concentrations range from 50 to 60 µg/m³, notably lower than the 100 to 200 µg/m³ observed in the 1-h maximum scenario. Elevated levels persist near emission sources during calm or low-wind conditions, but generally, areas northeast and southeast of primary emission sources are most affected due to prevailing wind patterns.

The dispersion patterns of $SO_2$ and $NO_2$ in Dong Thap province mirror those of TSP, with peak concentrations occurring near industrial facilities. Maximum 1-h concentrations reach 373.2 µg/m³ for $SO_2$ and 643.4 µg/m³ for $NO_2$, both significantly higher than their respective national standards of 350 µg/m³ and 200 µg/m³, indicating the potential pollution under extreme condition. The 24-h levels are considerably lower but, at 141.8 µg/m³ for $SO_2$ and 241.8 µg/m³ for $NO_2$, particularly in downwind areas. The southwest monsoon's moderate winds extend the impact area, dispersing pollutants over a broader region. Sa Dec city, with its high concentration of factories, experiences the most significant air quality impacts. However, the affected area remains limited to a small region downwind of the industrial center. Notably, at distances of about 1 km from emission sources, even under extreme emission scenarios, both $SO_2$ and $NO_2$ concentrations drop dramatically to less than 10 µg/m³, indicating rapid dispersion and dilution of these pollutants in the atmosphere.

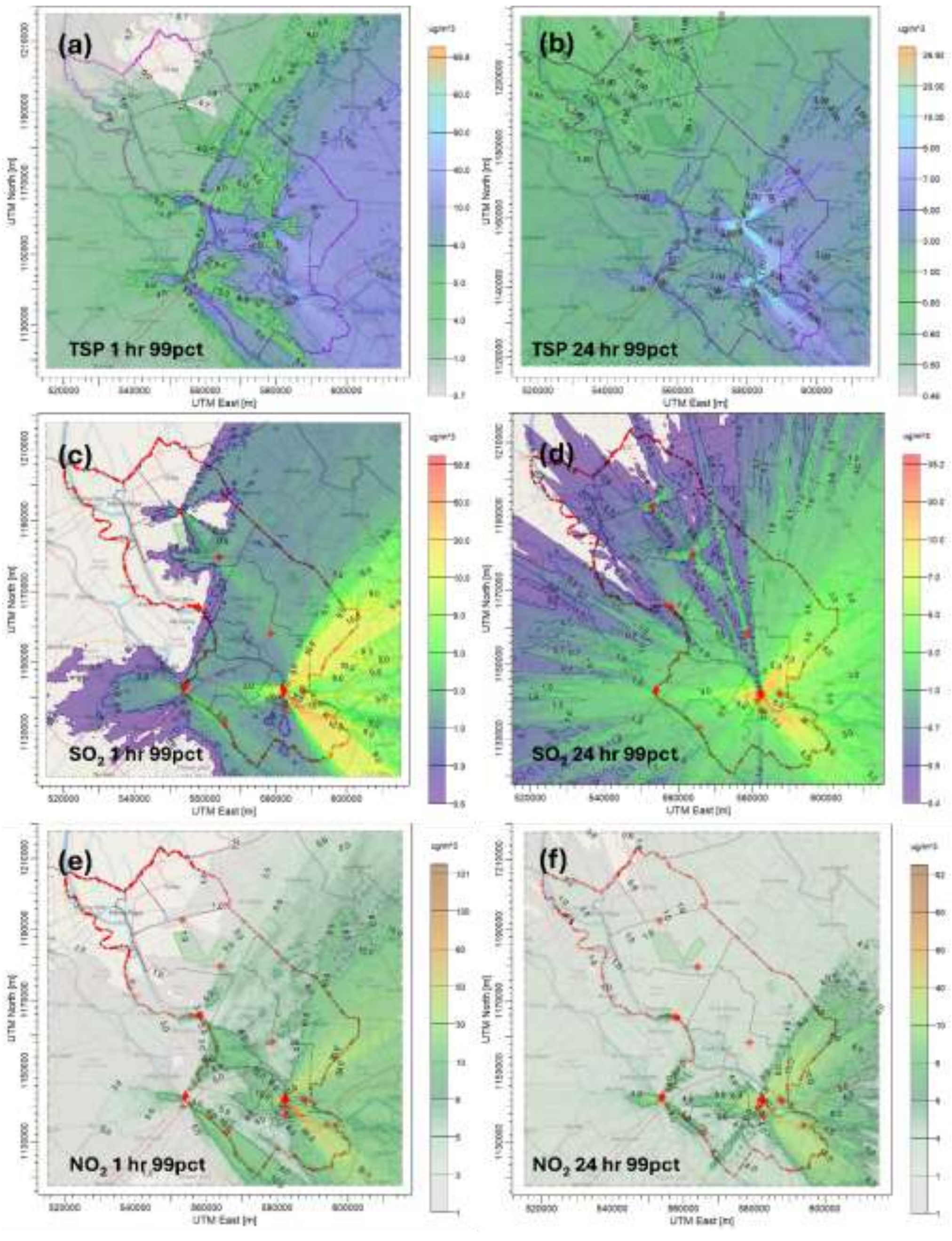


Figure 8. Dispersion events at the 99th percentile from stack emission sources: (a) 1-h TSP, (b) 24-h TSP, (c) 1-h $SO_2$, (d) 24-h $SO_2$, (e) 1-h $NO_2$, and (f) 24-h $NO_2$.

### *3.5. Characterization of Stack Emissions Dispersion at the 99th Percentile*

The results in Figure 8 show pollutant dispersion at the 99th percentile, representing a 1% probability of occurrence. In these extreme cases, 1-h concentrations of TSP, $SO_2$, and $NO_2$ reach localized peaks of 68.8, 58.8 and 101 µg/m³, significantly lower than the maximum values seen in the most severe scenarios (312, 373, and 643 μg/m³, respectively, as shown in Figure 7). The 24-h concentrations show a similar trend, with the highest TSP concentration near Sa Dec's industrial zone reaching 26.9 μg/m³, compared to 81 μg/m³ in the maximum scenario. While the worst cases show potential pollution risks in industrial areas, the 99$^{th}$ percentile concentrations remain below the limits set by QCVN 05-2023/BTNMT, indicating that severe pollution events occur less than 1% of the time, primarily during unfavorable climate conditions.

Figure 9 presents a seasonal analysis of maximum concentrations for three air pollutants (TSP, $SO_2$, and $NO_2$) in the center of Cao Lanh city, the area most impacted by stack emissions during extreme events. TSP shows the highest concentrations and widest variability, ranging from 24.2 to 208.8 μg/m³ in January. Peak TSP levels occur during January-February, averaging 113.4–128.4 μg/m³, corresponding to the dry season, while the lowest concentrations are observed in September-October, averaging 79.4–82.1 μg/m³, likely due to the wet season. The interquartile range (IQR) for TSP varies significantly, from 34.2–119 μg/m³ in September to 74.5–135.6 μg/m³ in January, highlighting the influence of wind patterns on pollutant distribution. $SO_2$ and $NO_2$ exhibit similar seasonal patterns but at lower concentrations. $NO_2$ has a maximum IQR of 8.4–18.5 μg/m³, and $SO_2$ has a maximum IQR of 9.6–21 μg/m³, both in January. The large daily variation patterns reflect seasonal meteorological influences on pollutant dispersion and accumulation.

### *3.6. Seasonal Variation of Daily Maximum Concentrations*

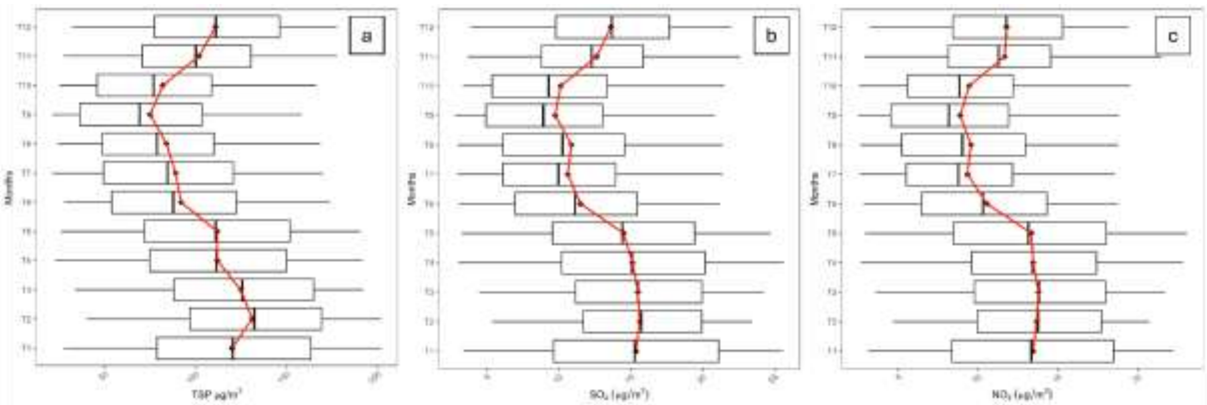


Figure 9. Seasonal variation of daily maximum concentrations of (a) TSP, (b) $SO_2$, and (c) $NO_2$ at the center of Cao Lanh city. The boxplots represent the interquartile range with the median shown as a vertical line, while the horizontal bars indicate the 10$^{th}$ and 90$^{th}$ percentiles. Mean values are marked with black dots, connected by a red line to illustrate seasonal trends.

### *3.7. Annual Average Distribution of Stack Emissions*

The annual average dispersion of stack emissions from major industries in Dong Thap province for 2021–2023, illustrated in Figure 10, reveals significant air quality impacts across the region. This scenario represents the cumulative sum of all hourly simulations, highlighting long-term areas most affected by stack emissions. Concentrations of TSP, $SO_2$, and $NO_2$ are notably higher near industrial zones, with peaks observed around major factories. While pollutant levels remain well below regulated limits, indicating that severe air pollution from stack emissions is rare, there is still a discernible impact on air quality in southern Dong Thap, particularly in Cao Lanh and Sa Dec cities. This study focuses solely on stack emissions and does not consider contributions from other sources, such as industrial, agricultural, and urban activities. Even with this narrow focus, localized pollution can occur under unfavorable meteorological conditions. Therefore, it is essential to develop management and mitigation plans to address the impacts from stack emissions. Implementing effective strategies that include regular monitoring, emission reduction technologies, and public awareness initiatives will be crucial in safeguarding air quality and promoting sustainable development in the region.

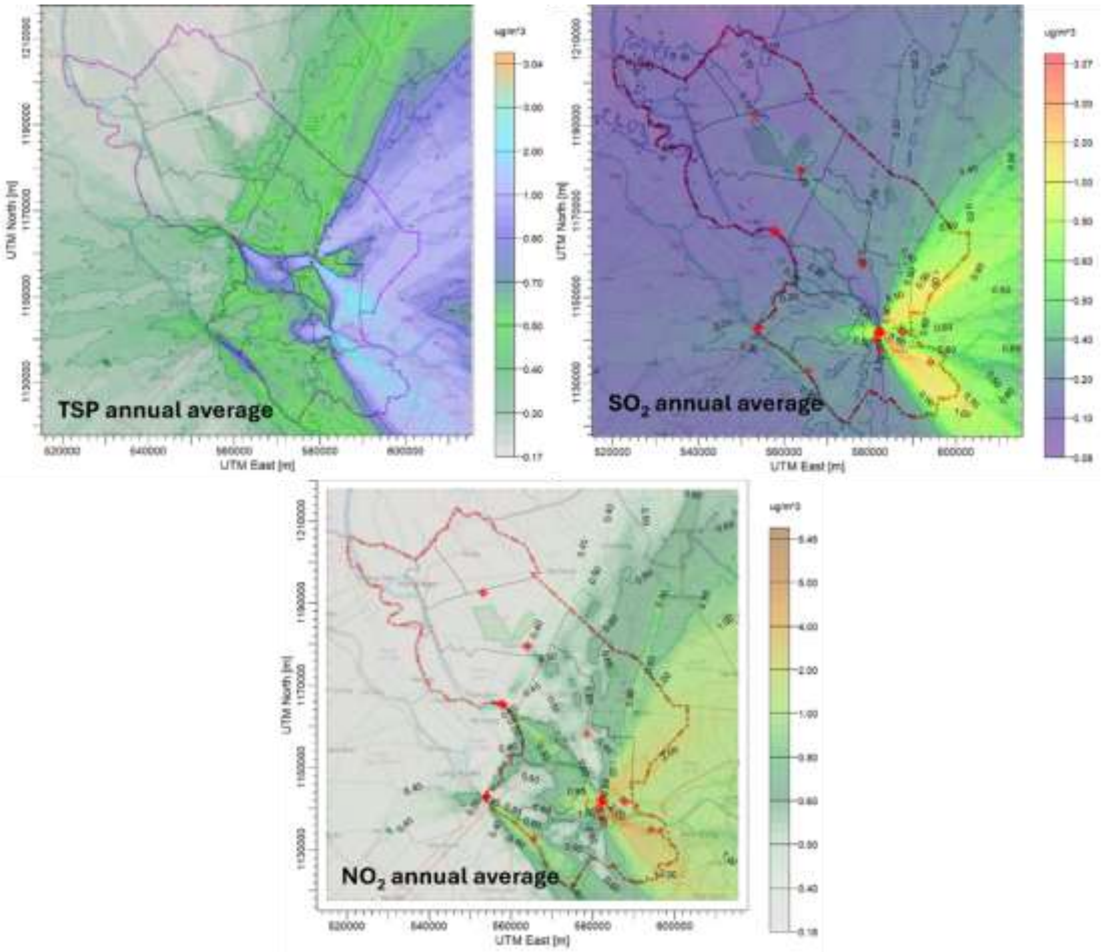


Figure 10. Annual average dispersion of stack emissions from major industries (2021-2023).

**4. Limitations and Uncertainty**

This study acknowledges several limitations and uncertainties. AERMOD is a dispersion model, not a full air quality model, and its calibration requires controlled field conditions, which were not feasible. While ERA5 meteorological data were validated using Can Tho Station measurements, local wind variations may introduce uncertainties. The 100 km × 100 km simulation domain exceeds AERMOD’s recommended range, but pollutant concentrations beyond 30 km were negligible. Additionally, only stack emissions were modeled, excluding other sources like traffic and residential combustion, which may lead to underestimations.

## 5. Conclusion

This study aimed to assess the impact of industrial stack emissions on air quality in Dong Thap province, focusing on TSP, $SO_2$, and $NO_2$. Using the AERMOD dispersion model and incorporating meteorological data from ERA5 reanalysis dataset, the study analyzed emissions from 19 major industrial plants with 36 emission stacks across the province from 2021-2023.

Validation with observed station data confirmed that the ERA5 dataset effectively captured regional wind and surface temperature patterns. The AERMOD results indicated that industrial stack emissions account for 30–70% of local pollution sources.The results reveal that while extreme pollution events are rare, industrial stack emissions do have a measurable impact on local air quality. Maximum 1-h concentrations reached 312 µg/m³ for TSP, 373.2 µg/m³ for $SO_2$, and 643.4 µg/m³ for $NO_2$, exceeding national standards in isolated cases. However, at the 99th percentile, concentrations were significantly lower, with 1-h peaks of 68.8 µg/m³ for TSP, 58.8 µg/m³ for $SO_2$, and 101 µg/m³ for $NO_2$, all below regulatory limits. Annual average concentrations showed a more dispersed pattern but still indicated localized impacts near industrial zones, particularly in Cao Lanh and Sa Dec cities. The terrain facilitates rapid pollutant dispersion, reducing localized pollution intensity but allowing pollutants to travel farther, potentially impacting neighboring provinces. Winds predominantly blow from the west-northwest to southwest at speeds ranging from 0.5 to 5.7 m/s, further contributing to the spread of pollutants toward areas like Vinh Long and Can Tho.

This study highlights the need for targeted air quality management in Dong Thap, particularly in industrial zones and downwind areas, where stack emissions can directly contribute to air pollution. To gain a more complete understanding of the region's air quality, follow-up studies should include other emission sources, conduct long-term monitoring, and assess potential health impacts on local populations.

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