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Air Pollutant Dispersion Pattern around Yoff, Dakar

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Abstract

Particulate matter (PM) with an aerodynamic diameter of 2.5 µm or less ($PM_{2.5}$) poses a significant threat to human health. This study employs the Gaussian model to simulate the dispersion of $PM_{2.5}$ in Yoff from 2018 to 2019. A total of 69 $PM_{2.5}$ samples were collected using the Gent stacked filter unit sampler, with an average concentration of $292.4 \pm 43.2\ \mu g \cdot m^{-3}$. The simulation was conducted under neutral atmospheric conditions (stability class D), following Pasquill's stability classification. The findings indicate that $PM_{2.5}$ disperses up to approximately 2,800 meters from the source. Higher concentrations were observed to the north (N) and North-Northwest (NNW), primarily due to the influence of sea salts and secondary sulphur, affecting locations such as Yoff Bay and the Yoff Tangor market. Additionally, traffic emissions from the West (W) and West-Southwest (WSW) contribute to increased pollution, impacting sensitive areas such as Philippe Maguilen Senghor Hospital, the Océan Hotel, and the military base. Further away, Grand Yoff and Parcelles Assainies are also affected by $PM_{2.5}$ dispersion. This study identifies road traffic and sea salt/secondary sulphur as the primary sources of $PM_{2.5}$ pollution in Dakar. These findings play a crucial role in air quality management in Yoff, enabling local authorities to forecast pollutant dispersion and implement measures to protect both the environment and public health.

Keywords

Health, Gaussian, Simulation, Pollution

1. Introduction

$PM_{2.5}$ ranks 6th for its impact on the global burden of disease, posing a major threat to public health [1]. Also known as fine PM, $PM_{2.5}$ can penetrate deep into the respiratory system, leading to severe health issues such as cancer, heart disease, and respiratory disorders [2]-[5]. Apart from its health impacts, $PM_{2.5}$ also has environmental consequences, such as contributing to haze formation and diminishing visibility [6]. Additionally, $PM_{2.5}$ contributes to climate change, with incomplete combustion releasing black carbon (BC), which can exacerbate global warming [7]. $PM_{2.5}$ primarily originates from anthropogenic sources, including industrial activities, combustion processes, tobacco smoke, and vehicle emissions [8] [9]. Furthermore, secondary $PM_{2.5}$ particles form in the atmosphere through complex chemical reactions between primary particles and precursor gases. The atmospheric lifetime of $PM_{2.5}$ ranges from a few days to several weeks [10].

Research focuses on identifying pollution sources and simulating their dispersion to reduce pollutant concentrations and mitigate their effects in cities. Dispersion models are essential for forecasting pollutant spread, guiding public policy, and helping urban planners protect the environment and public health while optimising resources [11]. To ensure accuracy, choosing the right dispersion model is crucial [12]. Available models, such as Box, Gaussian, and Lagrangian-Eulerian, vary in structure, complexity, and spatial-temporal dimensions [13]. The Gaussian model is widely used for pollutant dispersion studies, particularly in urban environments with simple topography [14]. However, its computational efficiency is limited in complex terrains and low wind conditions, affecting the accuracy of results, especially in coastal environments. Specifically, it struggles to accurately predict dispersion under low wind speeds, short source-receptor distances, or delayed pollutant transport [15] [16]. Despite these constraints, the Gaussian model remains a preferred choice due to its ease of use and computational efficiency, making it an effective option when resources are limited. It enables rapid and cost-effective simulations, well-suited for urban environments with moderate dispersion conditions. This study assumes a single point source for $PM_{2.5}$ emissions, neglecting the distributed nature of traffic and other sources that could significantly influence dispersion patterns. Unlike more sophisticated models such as Lagrangian-Eulerian models, the Gaussian model remains a valuable tool for preliminary dispersion studies, especially when data availability is limited [13]. Although wind data is used, the study lacks a comprehensive analysis of other relevant meteorological parameters (e.g., temperature, humidity, atmospheric stability), which can significantly affect $PM_{2.5}$ dispersion. The study considers only neutral stability conditions (class D), with limited justification for this assumption. This approach overlooks the potential impact of varying atmospheric stability on pollutant dispersion.

Yoff, a coastal town in Dakar, Senegal, has an estimated population of 120,000 and is experiencing rapid growth in industrial and agricultural activities, as well as a rise in vehicle numbers. This has led to environmental changes and a decline in air quality. Although the Air Quality Management Center of the Direction of Environment and Reserved Buildings monitors air quality in Dakar [17], and some research has been conducted in Senegal [18] [19], studies on pollutant dispersion in Yoff remain scarce. The lack of specific air quality data for Yoff highlights the need for further investigation. Thus, the main objective of this study is to model the dispersion of $PM_{2.5}$. An initial estimate of pollutant distribution will be obtained using the Gaussian dispersion model.

2. Materials and Methods

2.1. Sampling

Sampling was conducted in Yoff, located at 14.75389˚N and 17.46778˚W. This area, with a population of 120,000 covers approximately 15 km^2 and includes a hospital, a military airport, hotels, and printing and paint factories. The sampler was installed 2 km from the coast, beside a road, directly opposite printing works and paint factories. Each sampling session lasted approximately 24 hours. The sampling site is shown in Figure 1.

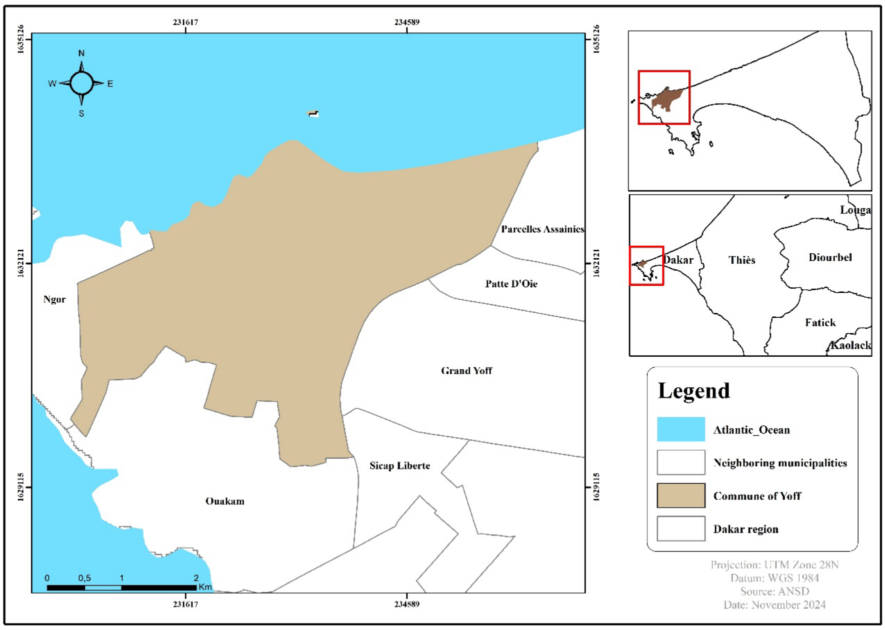

Figure 1. Location of the Yoff sampling site.

The collected particle samples effectively represented a larger urban area, as the air masses, regardless of direction, reached the collection points undisturbed. A low-volume sampler from the University of GAND was used for sample collection. Maenhaut [20] provide a detailed description of this sampler. Briefly, it operates at a flow rate of 16 L/min and collects $PM_{2.5}$ and PM_{10} using two successive 47 mm diameter filters. Particles larger than 10 μm were removed using a PM_{10} pre-impactor stage, positioned upstream of the stacked filter cassette. The sampler uses a diaphragm vacuum pump, enclosed in a special casing, and equipped with a needle valve, vacuum gauge, flow meter, volumetric counter, time switch (for interrupted sampling), and hour meter to regulate air intake.

Nucleopore polycarbonate filters (47 mm diameter, 0.4 μm pore size) were used to collect $PM_{2.5}$ [20]. To prevent hydration and contamination, the filters were placed in a desiccator after collection. Gravimetric quantification was performed using Sartorius microbalances (Secura and Quintix 26) with a precision of 10^{-5} g. The average of three measurements was used to determine the filter weights, provided that variations were below 0.5%.

A yearly measurement campaign was organised in 2018 and 2019 to gather $PM_{2.5}$ samples. Sampling took place twice a week, including both weekdays and weekends. This sampling protocol was chosen to maximise the diversity of contributions from various sources, a crucial factor for optimising the performance of source attribution models. During the 2018-2019 period, numerous samples were collected, and 69 $PM_{2.5}$ samples were selected for this study. Wind direction and speed data were obtained from the Air Quality Management Centre of the Directorate of Environment and Reserved Buildings [17].

2.2. Gaussian Dispersion Equation

The Gaussian model follows the laws of normal statistical distribution. Resolutions are represented in the vertical, crosswind, and downwind directions using a system of three-dimensional axes. Weighted by the wind speed at the emission site, the concentration of a pollutant is proportional to the emission rate from the source. The standard deviations of the Gaussian distribution function, primarily determined by air stability, local turbulence, and the distance travelled downwind, define the dispersion of a pollutant. In general, the model's axis is oriented to correspond to the predominant wind direction. The Gaussian distribution equation is presented as follows [21]:

$$C_{x,y,z} = \frac{Q}{2\pi u \sigma_y \sigma_z} \left\{ \exp\left[-\frac{(h-z)^2}{2\sigma_z^2} \right] + \exp\left[-\frac{(h+z)^2}{2\sigma_z^2} \right] \right\} \left\{ \exp-\left[-\frac{(y)^2}{2\sigma_y^2} \right] \right\} \quad (1)$$

where:

$C_{x,y,z}$ = Pollutant concentration as a function of downwind position (x, y, z);

Q = mass emission rate in g.s^{-1};

u = wind speed in m.s^{-1};

σ_y = standard deviation of pollutant concentration in the y (horizontal) direction;

σ_z = standard deviation of pollutant concentration in the z (vertical) direction

y = distance in horizontal direction;

z = distance in vertical direction;

h = effective stack height.

The coefficients σ_y and σ_y are functions of the downwind distance $\boldsymbol{x}$. These coefficients are determined using Equations (2)-(4):

$$\sigma_y = 465.11628x(\tan\theta) \quad (2)$$

where:

$$\theta = 0.017453293\left(c - d.\ln\left(x\right)\right) \tag{3}$$

$$\sigma_z = ax^b \tag{4}$$

x is in kilometers σ_y and σ_z are in meters; a and b depend on x.

The stability classes provided the foundation for establishing the values **a**, **b**, **c**, and **d** [22]. The Davidson-Bryant plume rise formula, given in equation 5 [23], was used to calculate the effective emission height of the source:

$$\Delta H = d\left(\frac{V_s}{u}\right)^{\frac{1}{4}}\left(1+\frac{\Delta T}{T_s}\right) \tag{5}$$

where:

ΔH = the rise of the plume above the stack;

d = the inside stack diameter;

V_s = stack gas velocity;

u = wind speed;

ΔT = the stack gas temperature minus the ambient air temperature (°K);

T_s = the stack gas temperature (˚K).

2.3. Dispersion Model: Structure and Configuration

The Python software was used to create the program. The dispersion of $PM_{2.5}$ released by stationary sources under various wind and atmospheric stability conditions was simulated using the Gaussian model. Basic parameter setup, source and aerosol customisation, Gaussian model-based pollutant concentration calculations, and result visualisation are all included in the code structure. We used a distance of 300 metres to study the local dispersion of $PM_{2.5}$ contaminants in Yoff. Based on the values given in **Table 1**, the simulation of $PM_{2.5}$ dispersion at Yoff is carried out, taking into account an emission rate of 2603 $Kg.s^{-1}$ and a wind speed of 16.31 $m.s^{-1}$. The situation, therefore, corresponds to a neutral condition (D) in terms of Pasquill's stability category. The following stability values were used to compute σ_y and σ_z : a = 34.459, b = 0.86974, c = 8.3330, and d = 0.72382 [24].

3. Results and Discussions

3.1. Concentration Levels of $PM_{2.5}$, Wind Speed, and Wind Direction

The $PM_{2.5}$ concentration levels, wind speed, and wind direction at Yoff throughout the 2018-2019 study period are summarised in **Table 1**.

Table 1. Summary of the data from the $PM_{2.5}$ sample.

	Concentration $PM_{2.5}$ ($\mu g.m^{-3}$)	*Wind Speed ($m.s^{-1}$)*	*Wind Direction (in degrees)*
Minimum	148 ± 8.195	9	28
Median	286 ± 33.418	16	236
Mean	292.4 ± 43.240	16.31	231.9
Maximum	495 ± 46.319	25	360

Table 1 shows that $PM_{2.5}$ concentrations ranged between 148 and 495 $\mu g.m^{-3}$ in Yoff. Similar $PM_{2.5}$ concentrations were found when our study was compared with earlier research [25]. The high $PM_{2.5}$ values obtained in Yoff are due to the contribution of traffic and industrial emission sources [26].

Our Gent stacked filter unit sampler was positioned two meters above the ground during our campaign. Equation (5) was used to determine the pollution plume's effective height, which was a very low 0.000035 m. For this reason, the dispersion of $PM_{2.5}$ pollutants was simulated at a height of two meters.

3.2. Wind Analysis

To analyse the wind direction distribution in Yoff during the 2018-2019 period, Figure 2 shows the wind rose.

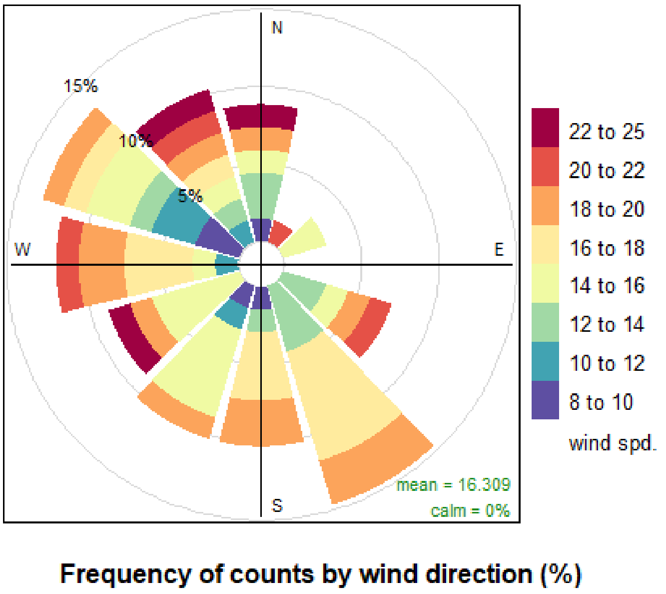

Figure 2. The wind rose in Yoff during 2018-2019.

The wind rose was created using R Openair software. Figure 2 shows the distribution of wind directions and speeds. The predominant wind direction is South-South-East (SSE), with wind speeds ranging from 18 to 20 m/s recorded 15% of the time. The West-Northwest (WNW) direction follows, with similar wind speeds, but only for around 13% of the time. Wind speeds in the westerly direction range from 20 to 22 m/s. Wind speeds exceeding 22 m/s are recorded, particularly in the N, NNW, and WSW directions.

3.3. Modelling Results

The aforementioned criteria (see section 2.3) were taken into account when simulating the dispersion of $PM_{2.5}$ pollutants at Yoff. Additionally, the dispersion of $PM_{2.5}$ from the Yoff source (14˚45′14″N, 17˚28′04″W) was accurately visualised using OpenStreetMap. Figure 3 illustrates this scenario.

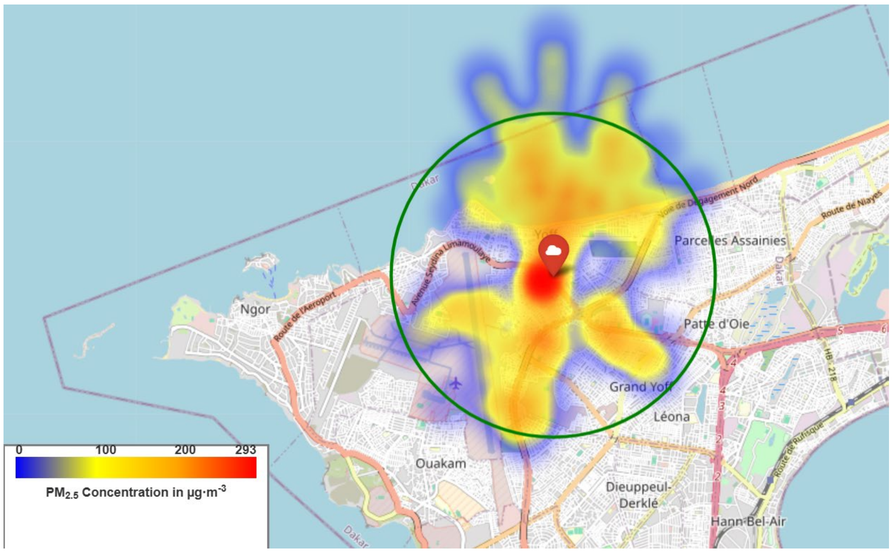

Figure 3. Dispersion of $PM_{2.5}$ patches in Yoff under stable conditions.

A black circle, symbolising the limit of the $PM_{2.5}$ dispersion area, surrounds a red dot on the map, indicating the pollution source along the road. While concentrations in the more polluted red and orange zones are higher, those in the yellow zones are closer to the average (312.37 $\mu g.m^{-3}$).

Due to sea salts and secondary sulphur compounds, which are recognised as key sources of pollution [25], the N and NNW directions, including the sea, Yoff Bay, and the 'Yoff Tangor' market, are characterised by high levels of $PM_{2.5}$ [25]. In this scenario, customers and traders at the fish market are particularly exposed to these $PM_{2.5}$ pollutants.

High concentrations are also found in the W and WSW directions due to heavy traffic. The Philippe Madelaine Senghor Hospital, the L'Océan Hotel, and the military airport are all located in this area, exposing medical personnel, patients, military personnel, and hotel guests to these $PM_{2.5}$ pollutants.

Beyond Yoff, the pollutant dispersion continues south (S) towards the North clearance, SSE towards the commune of Grand Yoff, and finally reaches the Parcelles Assainies in an East-Northeast (ENE) direction, with winds of 14 to 16 m/s.

4. Conclusions

This study used Python software to investigate the dispersion of $PM_{2.5}$ pollution in Yoff during the 2018-2019 period. The results showed that $PM_{2.5}$ dispersed up to 2,800 meters from the source, with a diffusion radius. They also revealed that Yoff Bay and the 'Yoff Tangor' market, located to the N and NNW of the pollution source, had high concentrations of $PM_{2.5}$ due to sea salts and secondary sulphur. Road traffic further contributed to pollution in the W and WSW directions, affecting sensitive sites such as the military airfield, the 'L'Océan' hotel, and the Philippe Madelaine Senghor hospital. Pollutants are dispersed as far as Grand Yoff and Parcelles Assainies, which are farther from Yoff. The study indicated that road traffic and sea salts/secondary sulphur are among the primary sources of pollution in Dakar. These findings align with the results of our previous survey on the distribution of pollution sources. However, there is no validation of the model results with independent measurements or more sophisticated models presented, raising concerns about the reliability of the predicted dispersion patterns.

By anticipating and minimising the dispersion of pollutants, these results can help local authorities better protect the environment and public health. However, this study did not cover the entire Dakar region. To obtain more representative and accurate results, it would be useful to repeat the study at several locations within the region and extend the analysis to other pollutants, such as methane and NO_x emissions.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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