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Emissions and trajectories of atmospheric pollutants from mobile sources in a Colombian intermediate city

Emisiones y trayectorias de contaminantes atmosféricos de fuentes móviles en una ciudad intermedia colombiana

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ABSTRACT: In this study, the emissions of criteria pollutants and greenhouse gases from mobile sources in the main streets of the city of Valledupar were estimated. A vehicular characterization of the streets studied was carried out, and the IVE model was implemented to estimate the emissions generated by automobiles; subsequently, scenarios of atmospheric transport routes of pollutants were analyzed with the HYSPLIT model. The results showed that in the case of pollutant criteria, motorcycles emitted the highest amount of CO and PM_{10}, and private cars the highest SO_x and NO_x emissions. For GHGs, private cars emitted the highest amount of CO_2 and N_2O, while motorcycles emitted the highest amount of CH_4. The trajectory scenarios for the days of the study were carried out during the peak hours of vehicular circulation, implementing meteorological data from the WRF model. The trajectories were evaluated in rainy periods of 2021 and 2022 and in the dry period of 2022. In the rainy period, it was observed that the transport routes of the pollutants were directed in a greater proportion towards the NE direction and the dry period towards the SE direction. With this, it was possible to determine which areas of the city could be the most affected by vehicle emissions from the roads studied.

RESUMEN: En este estudio se estimaron las emisiones de contaminantes criterio y gases de efecto invernadero provenientes de fuentes móviles en las principales vías de la ciudad de Valledupar. Se realizó una caracterización vehicular de las vías estudiadas y se implementó el modelo IVE para estimar las emisiones generadas por los automotores; posteriormente se analizaron escenarios de rutas de transporte atmosférico de los contaminantes con el modelo HYSPLIT. Los resultados mostraron que, en el caso de los contaminantes criterio, las motocicletas emitieron la mayor cantidad de CO y PM_{10} y los automóviles particulares las emisiones más altas de SO_x y NO_x. Para los GEI, los automóviles particulares emitieron la mayor cantidad de CO_2 y N_2O mientras que las motocicletas fueron las que emitieron la mayor cantidad de CH_4. Los escenarios de trayectoria para los días de estudio se realizaron en las horas pico de circulación vehicular implementando datos meteorológicos del modelo WRF. Las trayectorias se evaluaron en periodos de lluvia de los años 2021 y 2022 y en un periodo seco del año 2022. En el periodo de lluvia se observó que las rutas de transporte de los contaminantes se dirigían en mayor proporción hacia la dirección NE y en el periodo seco hacia la dirección SE. Con esto se pudo determinar qué áreas de la ciudad pueden ser las más afectadas por las emisiones vehiculares de las vías estudiadas.

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1. Introduction

Currently, air pollution in urban areas around the world is mainly caused by mobile sources. The World Health Organization (WHO) estimates that one in eight of total

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global deaths is due to air pollution. In countries like Colombia, the National Planning Department (DNP) estimated that in 2015, the effects of this phenomenon were associated with 10,527 deaths and 67.8 million symptoms and illnesses. Additionally, it is estimated that Colombia's economic expenses related to environmental pollution increased from 1.1% of the Gross Domestic Product (GDP) in 2009 to 1,593% of the GDP in 2015 (15.4 billion pesos) [1]. In main cities in Colombia, such as Bogotá and Medellín, the contribution of vehicles to pollutant emissions is 78% and 81%, respectively [2, 3]. Intermediate cities in Colombia, such as Valledupar, have significantly increased their registered vehicle fleet, which has grown by 74% from 2008 to the present [4, 5] and the evasion of mechanical and pollutant emission technical inspections (RTMyEC) is 57%. According to other studies, it is shown that the type of combustion used generates a great impact, for example, the exhaust pipe for spontaneous ignition engines (Diesel) [6].

To carry out this research, the roads with the highest vehicular flow must be identified, and a meteorological characterization of the study site must be carried out. The International Vehicle Emissions (IVE) software implemented, which is used by the Environmental Protection Agency (EPA) is designed to estimate motor vehicle emissions [7]. To analyze the transport of pollutants and greenhouse gases (GHG) in the atmosphere, the Hybrid Single Particle Lagrangian Integrated Trajectory (HYSPLIT) model will be run [8, 9]. This software estimates the behavior of air masses in the atmosphere, which will determine the behavior of pollutants emitted by mobile sources in the city of Valledupar.

This work aims to contribute to the city of Valledupar by studying the criterion of pollutants and GHG emissions generated by mobile sources circulating in the city. This study will serve as a baseline for future research.

This article is an extension of the work initially presented at the International Congress EXPO-Ingenieria 2022 [10].

2. Data and methodology

2.1 International Vehicle Emissions (IVE) model

The IVE model was designed to estimate emissions from motor vehicles. Its prime purpose is for use in developing countries. The model predicts local air pollutants, greenhouse gas emissions, and toxic pollutants [7]. On the other hand, some studies show good qualifications for the use of the IVE model in terms of worldwide diffusion, accuracy of the results, easy implementation, and a friendly model with the results [11, 12].

Identification of the streets with the highest vehicular influx

In our study, different field visits were carried out, where a visual inspection was carried out, and the roads on which more vehicles transit were determined. Therefore, the conclusion was reached to choose nine (9) streets (see Figure 1). Two campaigns were carried out, the first from October 14 to 16, 2021, on the roads:

- Ave Calle 44, Ave Carrera 19, Ave Sierra Nevada.

The second included the days 22 to 24 and 26 to 28 September 2022, on the roads:

- Ave Carrera 9, Ave Carrera 7A, Ave Carrera 4, Ave Calle 6, Ave Calle 16, Ave Fundación.

Figure 1 Main streets of the city of Valledupar. First campaign: [1, 6, 9]; second campaign: [2–8]

Vehicle counts at the study points

Vehicle counts were carried out with the video recordings obtained. For 2021, all the hours of the video recordings were analyzed, from 8:00 Am to 6:00 Pm, while for 2022, a sample of 20 minutes was taken from each recorded hour [13] from 7:00 Am to 7:00 Pm. This analysis served as the basis to complete the behavior of the vehicular flow of the city of Valledupar in a week from Monday to Saturday. This procedure was validated with the registered behavior of the vehicular flow of the year 2021.

Obtaining of vehicular bins

They were obtained with the Speed Emissions Evaluation software, which is provided as an extra on the same IVE model page [14]. For its use, it was necessary to carry out an analysis of speed, altitude, coordinates, and distance traveled second by second in each of the streets. These data were collected thanks to a free-to-use App Avenza Maps [15]. It should be noted that a georeferenced map of the city of Valledupar was created for the analysis of the aforementioned criteria.

Determination of starting patterns

Taking into account that the Soak Bins are the distribution of time given as a percentage in which the engine was kept off before each game, 100% was established in the 15-minute Bin because the circulation of the street is continuous.

Vehicle technology

For the study, 15 vehicle types were characterized, in order to know the type of fuel, vehicle injection system and physical size, which will serve as the basis for choosing the most appropriate vehicle technology in the fleet file of the IVE model. The fuel technical data of gasoline and diesel was obtained from Ecopetrol S.A [16, 17]. This was corroborated using Resolution 40103 of 2021 [18], which establishes the general characteristics of the fuel for Colombia.

Environmental characteristics of the study area for the IVE model

The average temperature and relative humidity data of Valledupar introduced to the IVE were 28.5 C° and 67.2%, respectively; these were provided by IDEAM [19], and the altitude of 169 M.A.S.L was taken from the POMCA Formulation of the Guatapurí river [20].

2.2 Weather Research and Forecasting Model (WRF)

The meteorological data of the study area were obtained through simulations of the WRF model [21]. The WRF model simulations have been widely used for air quality research in Colombia during the last few years due to the advances in computational development [22–24]. The days of the vehicular counting campaigns were simulated by choosing three nested domains of 9, 3, and 1 kilometers; this last domain covered the entire city of Valledupar and was chosen for trajectory analysis. Days with dry conditions were also simulated to compare with gauging days, which were carried out in wet periods. In addition, the WRF data was validated with the data of the surface stations located in the city.

2.3 Hybrid Single Particle Lagrangian Integrated Trajectory (HYSPLIT)

Trajectory calculation

The model calculation method is a hybrid between the Lagrangian approach, which uses a moving reference frame for advection calculations, and the Eulerian approach, which t uses a fixed three-dimensional grid as a reference frame for diffusion calculations to calculate pollutant concentrations in the air. In calculating the trajectories of the model, the advection of a particle or puff is calculated from the average of the three-dimensional velocity vectors [25]; Equations (1) and (2) represent the base calculation of the trajectory model:
The first guess 3-D position is

$$\mathrm{P'(t+\Delta t)=P(t)+V(P,t)\Delta t} \tag{1}$$

The final position is

$$P(t+\Delta t)=P(t)+0.5\left[V(P,t)+V\left(P',t+\Delta t\right)\right]\Delta t \tag{2}$$

Where P(t) is the position of the vector at an initial time, V is the velocity, and Δt is the time period in which the integration of Δt can vary during the simulation. In this calculation, HYSPLIT implemented a stability parameter (Equation (3)). Thus, it is calculated from the requirement that the advection distance per time step must be less than the grid spacing. The maximum transport speed is determined from the maximum transport speed during the previous hour. The time steps can vary from 1 minute to 1 hour and are calculated from the relationship [26].

$$\mathrm{Umax}(\text{ grid } - \text{ units min } -1)\Delta t(\mathrm{min}) < 0.75(\text{ grid } - \text{ units }) \tag{3}$$

Where U_{max} is the maximum speed in grid units, this criterion is given in order to avoid erroneous simulations due to a lack of data in the meteorological fields [26].

Input data

Once the meteorological data from the WRF data files have been processed, it is possible to generate the execution of the HYSPLIT trajectory model [27]. The trajectories were modeled on the days 14, 15, and 16 of the month of October 2021 (vehicle capacity campaign 1); and the days 22, 23, 24, 26, 27, and 28 of the month of September 2022 (vehicular capacity campaign 2) and 13,14,15 of the month of January of the year 2022 (period with dry conditions) seeking the representation of the hourly variability of the air parcels selected, starting from the location of the corresponding study paths, each one was calculated in one-hour intervals, in the first campaign it was from 8:00 Am to 9:00 Am and from 6:00 Pm to 7:00 Pm. In the second campaign, the variation was from 7:00 Am to 8:00 Am, in both campaigns, the simulations were carried out at a height of 10 m at ground level in order to observe the dispersion at the local level.

3. Results

3.1 Emissions from mobile sources in the main street of the city of Valledupar

Considering all the data on the vehicle capacity, it was possible to know which of the streets have the highest vehicular traffic, obtaining Ave Calle 16 (351550), Ave Fundación (310324), Ave Calle 6 (233170), Ave Calle 44 (210645), Ave Carrera 7A (203022), Ave Carrera 9 (187726), Ave Carrera 19 (177881), Ave Sierra Nevada (165112), Ave Carrera 4 (158000). (See Figure 2).

Likewise, comparing the data obtained in 2021 and 2022, the variation of each typology was analyzed, finding very small variations, which shows us that after 1 year, the city's vehicle fleet maintains a constant flow and serves to determine results for subsequent years. (see Figure 3).

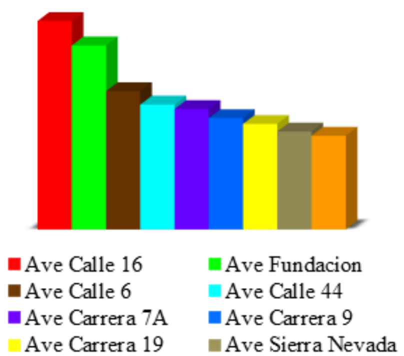


Figure 2 Vehicular traffic on the study street

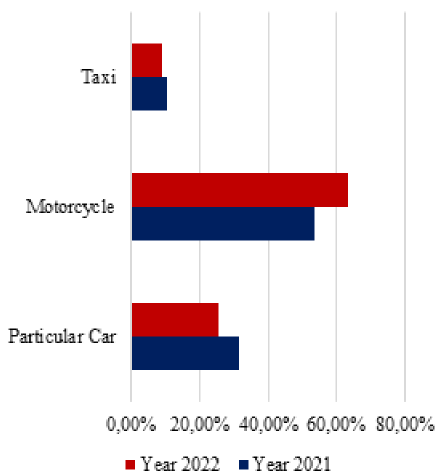


Figure 3 Variation of vehicular traffic between 2021 and 2022

In the same way, it was possible to know which type of vehicle travels the most on each street individually (see Figure 4). Based on this information, it is evident that motorcycles are the ones with the highest presence in the city are about 60.6%, Car (Private) 27.1%, and taxis 9.4% while the rest of the types are less than 1%.

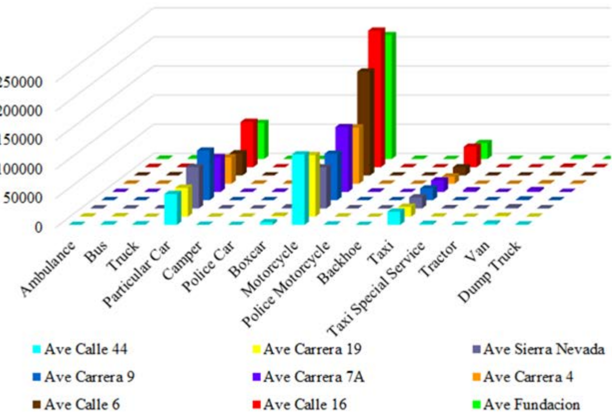


Figure 4 Number of vehicles in each typology, for each study street

In the results obtained with the IVE model for criteria pollutants (CO, NO_x, SO_x PM_{10}) and GHG (CO_2, N_2O, CH_4), we can see that in the criteria pollutants, CO is the one that is producing the most in the city, about 555822 Kg with an average of 97.4% (see Figure 5), while in greenhouse gases, CO_2 is 504995 Kg with an average of 95.1% (see Figure 6) in one week of study for both cases.

It was analyzed which are the vehicular typologies that can contribute the most to each one of the pollutants, finding that for CO (criteria pollutants) are motorcycles with 76.9%, while for CO_2 (GHG) are private cars with 46.1%.

In the same way, if we analyze the number of vehicles that circulate on the street (see Figure 2), it does not guarantee that it is the one that generates the most pollutants, as we can see in Figure 7. This is because there may be a type of vehicle with few vehicles with a high impact.

Observing that CO and CO_2 are the pollutants that the mobile sources generate the greatest amount, we proceeded to see their hourly behavior, noting that throughout the day, they have similar behavior with an increase in peak hours (see Figure 8)

3.2 Trajectory of the movements of the air masses in the different campaigns

The HYSPLIT model estimated the behavior of air movement where the pollutants (CO, PM_{10}, NO_x, SO_x,

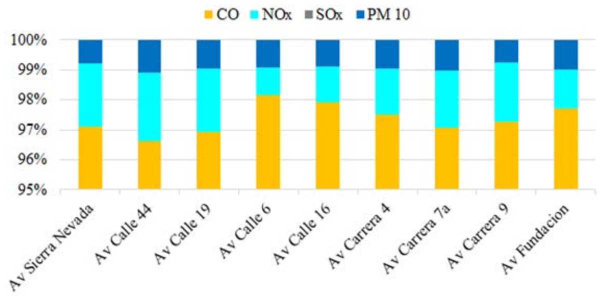


Figure 5 Distribution of criteria pollutant emissions in each of the streets

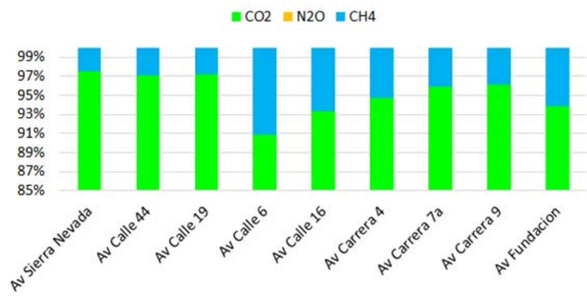


Figure 6 Distribution of greenhouse gas emissions in each of the streets

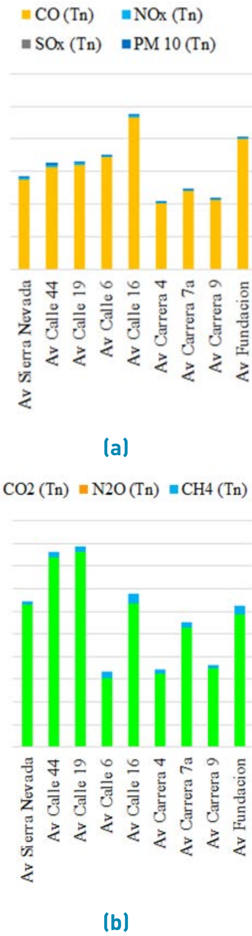


Figure 7 Emissions of pollutants per street. a) criteria pollutant b) greenhouse gases

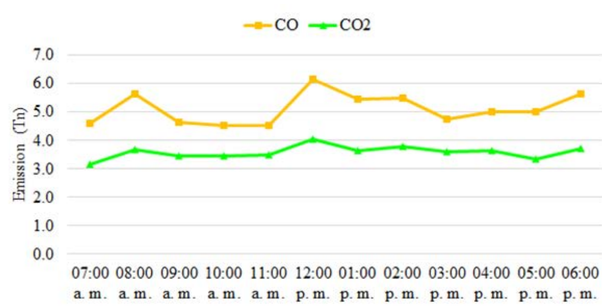
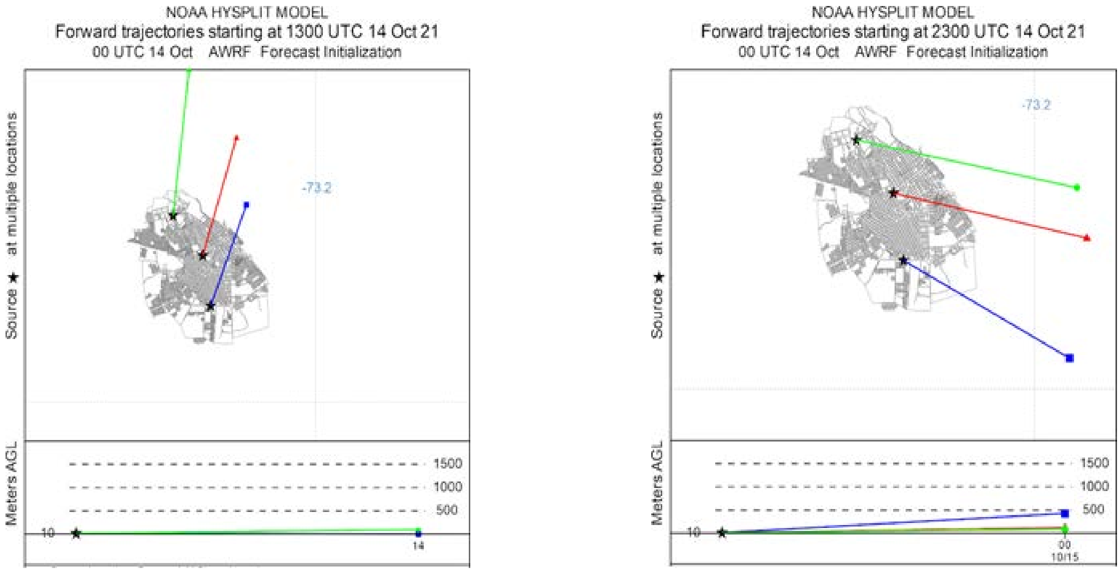


Figure 8 Hourly behavior of CO and CO_2 emissions, Observing an increase in peak hours

CO_2, N_2O, and CH_4) emitted in the study streets are transported. The model was simulated for the days 14, 15, and 16 of the months of October; A total of 18 trajectory maps were obtained. For the trajectory maps, three emission points were established on the study roads (Ave Sierra Nevada, Ave Carrera 19, and Ave Calle 44). On days 14, 15, and 16, it was observed that the trajectories were directed mainly towards the east of the city, as can be seen in Figure 9.

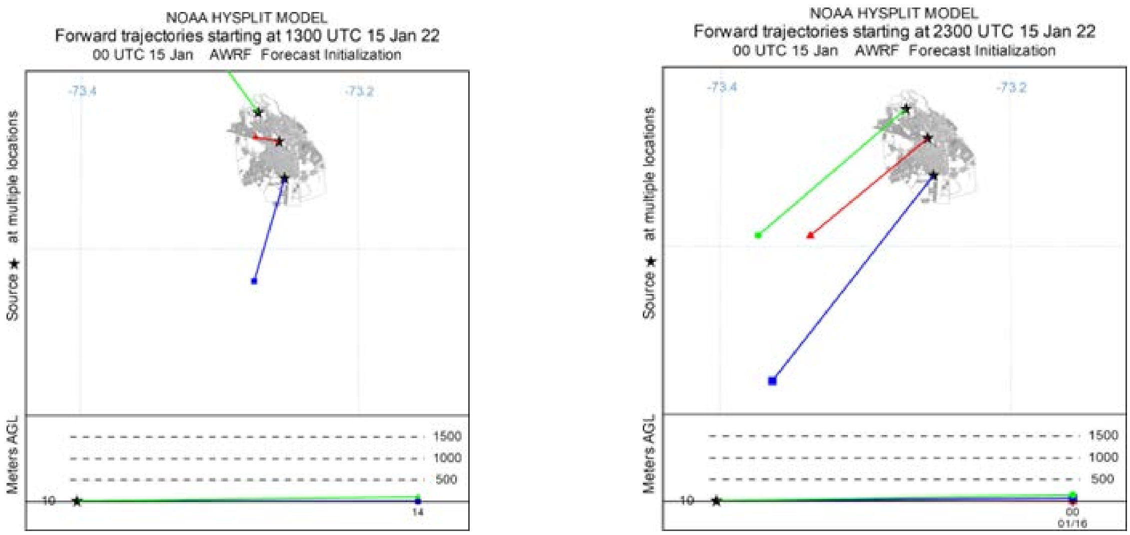
In the days of the study in October, the trajectories had a predominance towards the eastern part of the city, in which residential complexes, recreational parks, hospitals, restaurants, commercial premises and educational institutions are present, and during peak vehicular hours between 8:00 Am to 9:00 Am and 6:00 Am to 7:00 Pm, also in the days 13, 14, 15 of January 2022 three different days were taken to observe the behavior of these trajectories (see Figure 10) are evidenced in the following figures have a change in your direction compared to the October study days.

The figures show that in the study days of January trajectories (see Figure 10), this movement of air masses is directed mainly towards the west and southwest of the city; likewise, it is evident that the trajectories have a longer horizontal route, because the directions of the wind in Colombia are affected by the movement of the intertropical Convergence Zone (ITCZ) and the influence of the trade winds, which blow mainly from the northeast and the southeast [28]; these vary in the city depending on the season, in January northeasterly winds predominate, these emissions will be directed towards the west and south, where different residential areas, hospitals, and schools are located. In addition, the highest urban growth in the city is taking place in this area.



(a) **(b)**

Figure 9 The trajectories of October 14 at (a) 8:00 UTC-5 and (b) 18:00 UTC-5. The green trajectories are Sierra Nevada Avenue, the red one is Carrera 19 Avenue, and the blue one is Calle 44 Avenue

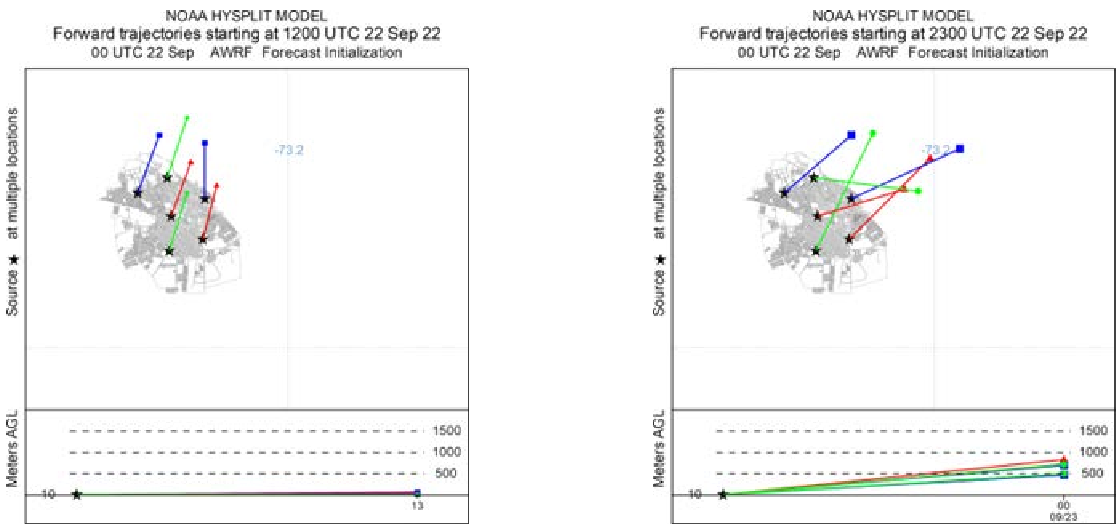


(a) **(b)**

Figure 10 The trajectories of January 15 at (a) 8:00 UTC-5 and (b) 18:00 UTC-5. The green trajectories are Sierra Nevada Avenue, the red one is a Carrera 19 Avenue and the blue one is Calle 44 Avenue

The second campaign of the capacity was carried out in 6 different study streets (Ave Carrera 9, Ave Calle 16, Ave Fundación, Ave Calle 6, Ave Carrera 7a, and Ave Carrera 4) during a week in September. A total of 72 trajectory maps were obtained during this week; their behavior was similar to the days studied in October: these emissions were directed to different areas of the city, but mainly to the east and northeast of the city, as indicated in Figure 11.

Figure 11 shows that through the movement of the air masses, the emissions in the study streets are affecting mainly the eastern and northeastern areas; a brief influence is also evident towards the western and northern areas; this occurs during the hours of 7:00 AM to 8:00 AM, in the time interval from 6:00 PM to 7:00 PM, the affectations occur mainly in the western and northwestern areas, a brief influence is also evident towards the eastern and northeastern areas.



(a) (b)

Figure 11 Trajectory of September 22 at (a) 7:00 UTC-5 and (b) 18:00 UTC-5 in the 6 different study tracks (Carrera 9 Avenue, Calle 16 Avenue, Ave Fundación, Calle 6, Carrera 7a Avenue, and Carrera 4 Avenue) in their corresponding locations as shown in Figure 1

The multiple trajectories carried out in the different months show that, on many occasions, the transport of pollutants close to ground level can cause negative impacts on human health. In the afternoon, the trajectories have a longer journey compared to the simulated hours in the morning, and this is because atmospheric instability occurs in the city in the afternoon.

4. Conclusions

The analysis of vehicular traffic in the city of Valledupar made it possible to identify the most congested roads in the city. It also showed that motorcycles are the ones with the highest influx are about 60.6%, Car (Private) 27.1%, taxis 9.4% while the rest of the types are less than 1%.

It was observed that the trade winds coming from the southeast have dominance in the circulation of atmospheric pollutants for the months of study: it should be noted that the influence of the North-East trade winds are the ones that predominate in the city of Valledupar. The input data in the HYSPLIT model were chosen in such a way that the trajectories during different seasons (dry and wet) were known to know and review the behavior of the pollutants.

The study showed that the distributions of the trajectories of October and September found in different areas of the city, but they generally occur in the east and northeast, where residential groups, hospitals, and commercial premises are located. In January, these air masses are transported to the west and southwest, thus affecting mainly homes and educational institutions.

The HYSPLIT trajectory model is linked to the meteorological conditions of the study area, which were obtained from the WRF meteorological model that represents the meteorological behavior of the study domain. Due to the satisfaction of the results with the HYSPLIT model, its use is recommended for further studies.

The interpretation of the trajectories of the movements of the air masses as a territorial planning tool framed for Colombia is a new perspective that can be very useful for establishing Land Management Plans and decision-making, starting from the perspective of the behavior of air pollution in different cities.

5. Declaration of competing interest

We declare that we have no significant competing interests, including financial or non-financial, professional, or personal interests interfering with the full and objective presentation of the work described in this manuscript.

6. Funding

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7. Author contributions

U. A. Bush Estimation of polluting emissions through the IVE model, data analysis and complementary information, A. A. Murillo HYSPLIT software modeling, meteorological analysis and additional data, J. L. Rodríguez Meteorological Modeling, data analysis, L. C. Díaz Data analysis, L. C. Angulo Data analysis.

8. Data availability statement

The authors confirm that the data supporting the findings of this study are available within the article [and/or] its supplementary materials

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