Geoscience Frontiers xxx (xxxx) xxx

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Geoscience Frontiers

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Research Paper

# Estimation of the impact of biomass burning based on regional transport of $PM_{2.5}$ in the Colombian Caribbean

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## ARTICLE INFO

*Article history:*
Received 10 September 2020
Received in revised form 17 January 2021
Accepted 23 January 2021
Available online xxxx

Handling Editor: M. Santosh

*Keywords:*
Biomass burning
Particulate matter
HYSPLIT
Dispersion model
Remote sensing

## ABSTRACT

Deterioration of air quality due to the increase in atmospheric emissions from biomass burning (BB) is one of the major environmental problems worldwide. In this study, we estimated the contributions of BB to $PM_{2.5}$ concentrations in the municipalities of Soledad and Malambo located in the Colombian Caribbean. The evaluation period ranged from February 24 to March 30, 2018, a period with a high number of BB events recorded in the surroundings of the evaluated sites. The contribution of BB to the two sampling sites was estimated using the Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) dispersion model with forwarding trajectories from each of the burning points identified by satellite images ($n = 1089$). The $PM_{2.5}$ emissions were determined using the fire radiative power (FRP), obtained by remote-sensing data, and corresponded to the radiant energy released per time unit by burning vegetation. The average $PM_{2.5}$ concentrations during the evaluation period were 19.91 $\mu g/m^3$ for Soledad and 22.44 $\mu g/m^3$ for Malambo. The average contribution of BB to these municipalities was 22.8% and 28.8%, respectively. The methodology used in this study allowed to estimate the contribution of this important source without knowledge of a previous tracer of BB, thereby increasing the use of the proposed procedure worldwide. This information would enable the implementation of effective mitigation, thereby diminishing the adverse impact of $PM_{2.5}$ on the health of the population.

## 1. Introduction

Biomass burning (BB) is defined as the uncontrolled burning of flammable vegetation, including wood, trees, and grass, over a part of an area or the entire area. BB is prevalent in all regions of the Earth and is directly or indirectly linked to human activities (IUFRO – International Union of Forest Research Organizations, 2018). This generates significant environmental, economic, social, and health-related issues worldwide due to the toxic emissions (Lai et al., 2019; Ramírez et al., 2019; Silva et al., 2019; Oliveira et al., 2020; Rönkkö et al., 2020).

The emissions caused by BB have been associated with the pollutants responsible for climate changes such as black carbon, carbon dioxide, carbon monoxide, nitrogen oxides, and $PM_{2.5}$ (Prato and Huertas, 2019; Silva et al., 2020a). The effects and contributions of BB have been studied by considering the regional transportation of pollutants, which increases the concentrations of a variety of pollutants (Wang et al., 2018; Rojas et al., 2019). Compared with other methods, the use of remote-sensing tools enables large-scale (regional or continental) evaluation with real-time data (Pereira et al., 2017). Furthermore, most of these tools are cost-effective or freely available (Amegah, 2018).

Although atmospheric contaminants are monitored continuously worldwide, several places, especially developing countries, have just started the process, as in certain regions of the Colombian Caribbean. However, it is essential to highlight that in addition to obtaining the information provided by this type of monitoring, it is important to know, which sources emitted these contaminants, whether natural and/or anthropogenic sources, for example, the contribution of BB to $PM_{2.5}$ concentrations. To obtain this type of information, expensive and tedious processes are used, and, therefore, the development of more practical, rapid, and easy methods should be encouraged (Querol et al., 2007; Schneider et al., 2015).

In this regard, the present study aimed to integrate the information obtained from the location of burning points identified by satellite images, the intensity of these recorded burnings (which represented the emission factor and was obtained from the FRP factor – fire radiative power and corresponded to the radiant energy released per time unit

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https://doi.org/10.1016/j.gsf.2021.101152

Please cite this article as: J. Bolaño-Truyol, I.L. Schneider, H.C. Cuadro, et al., Estimation of the impact of biomass burning based on regional transport of PM2.5 in the Colombian Ca..., Geoscience Frontiers, https://doi.org/10.1016/j.gsf.2021.101152

by the burning vegetation) and the use of a dispersion model (HYSPLIT) to estimate the impact of BB.

The Colombian Caribbean presents an intra-annual cycle of BB events, especially between December and March, corresponding to the dry period. Moreover, increased $PM_{2.5}$ concentrations are observed here due to the impact of these processes (Hoyos et al., 2017). The problem is more serious in the municipalities of Soledad and Malambo, located in the Colombian Caribbean, primarily due to the burning events in the Isla Salamanca Park, a natural mangrove reserve located in the surroundings of these municipalities (Ramírez et al., 2020; Silva et al., 2020b). This occurs continuously, especially during the dry period due to the uncontrolled burning of vegetation to obtain territories for agriculture or criminal acts. This study determined the contribution of biomass burning to the concentrations of $PM_{2.5}$ in the urban and industrialized municipalities of Soledad and Malambo, located in the Colombian Caribbean. The contribution was determined by considering the forward trajectories from the burning points using remote-sensing tools and the HYSPLIT dispersion model.

## 2. Methodology

### 2.1. Study area

The municipalities of Soledad and Malambo are located in the north of Colombia, at altitudes varying from 5 to 68 m.a.s.l., with 553,984 and 119,920 inhabitants, respectively (DANE – Departamento Administrativo Nacional de Estadística, 2018). These areas have an average annual temperature of 28.3 °C and 28.9 °C, respectively, with an average annual precipitation of 759 mm and 1277 mm, respectively. The main economic activities in these areas focus on four productive sectors, namely, industry, services, commerce, and transport, with manufacturing and metalworking industrial activities and the production of food and beverages, clothing, and chemical substances being the most important (Barranquilla, 2016). Moreover, two highways cross these two municipalities, and the largest airport in the Colombian Caribbean is located in Soledad. The PIMSA industrial park is located in Malambo.

The BB contributions in Soledad and Malambo municipalities were evaluated between February 24 and March 30, 2018 (Fig. 1). In these sites, the $PM_{2.5}$ concentrations were continuously determined at two sampling sites: the Environmental Protection Agency *Establecimiento de Desarrollo Urbano y Medio Ambiente of Soldedad* (EDUMAS) building (10°55′38.39″N, 74°46′17.82″W) and the Secretary of Transit and Transportation of Malambo building (10°51′42.30″N, 74°46′26.07″W). Both buildings have two floors, with their own Thermo Scientific 5014i Beta Continuous Ambient Particulate Monitor located on the roof.

The selected period corresponded to the dry season, with continuous burning processes occurring in this region during this period. Because of the direction of the predominant winds, burning points in the eastern region significantly affected the $PM_{2.5}$ concentrations

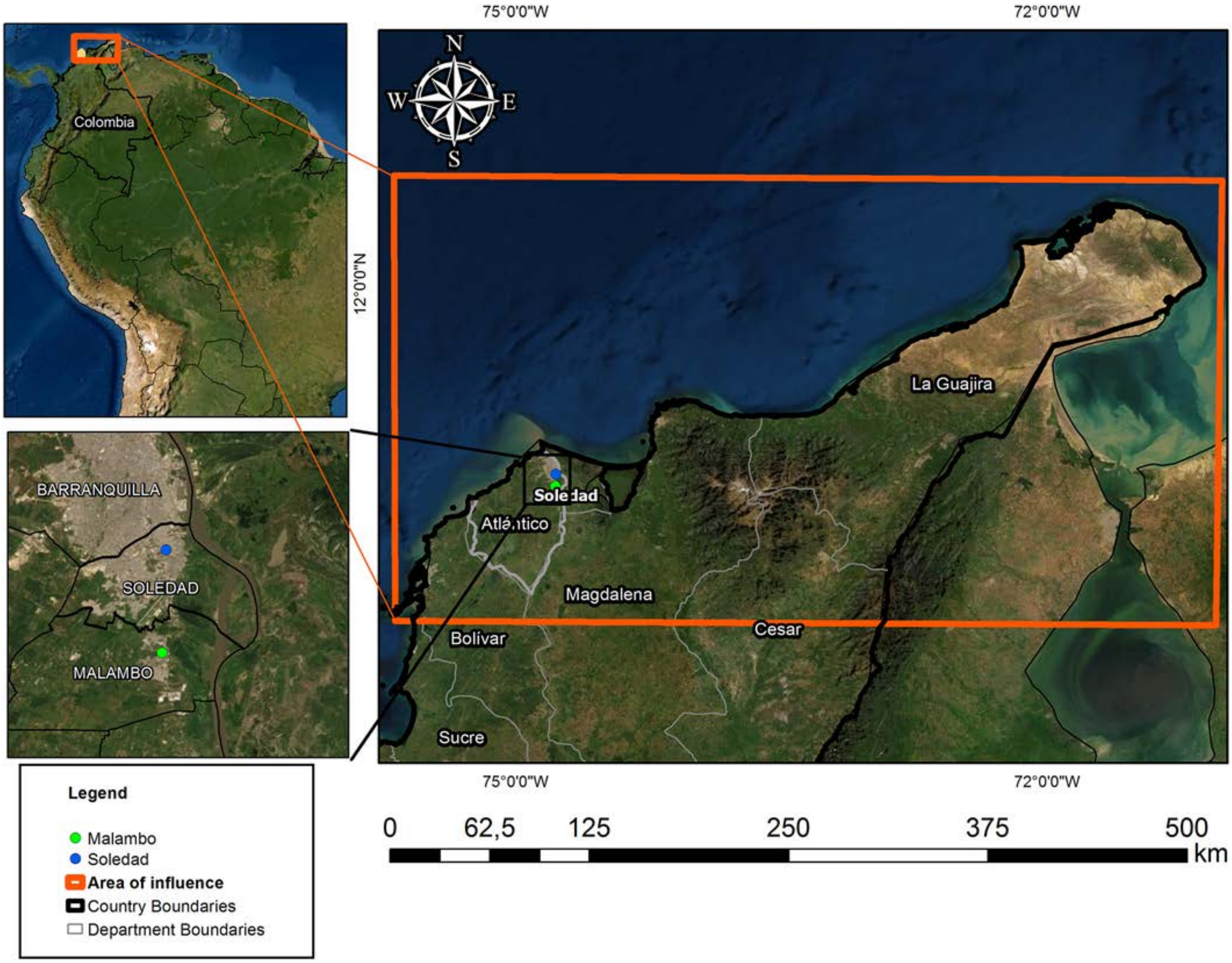

**Fig. 1.** Location of the study area and the area of influence considered.

(Supplementary Material). Thus, the regional transportation of $PM_{2.5}$ emitted by the burning from different departments of the Colombian territory, up to the border with Venezuela, was studied.

### 2.2. Identification of burning points

For the identification of burning points, the results obtained from the *Queimadas* platform of the National Institute of Space Research (INPE) from Brazil were used (Supplementary Material). Superficial temperature anomalies were identified and associated with burning points, and the fire radiative power (FRP) of each of these points was considered. FRP data are retrieved from a set of geostationary satellites and are theoretically a function of fire size and fire temperature. This parameter is linearly related to biomass consumption and helps to improve the estimation of biomass burning emissions (Li et al., 2018).

### 2.3. Calculation of $PM_{2.5}$ emissions

Biomass consumption is conventionally estimated as the product of the burned area, fuel load, combustion completeness, and burn severity. This last parameter is a qualitative metric that reflects the degree of consumption of organic matter from fire and relates to changes in the living and dead biomass, soil exposure, fire byproducts (char and ash), and fire effects (e.g., scorch height) (Li et al., 2018). However, obtaining information regarding some of these parameters can be difficult. Therefore, we applied the methodology that associates the biomass consumption and total emitted fire radiative energy (FRE). Wooster (2002) demonstrated a linear relationship between fuel consumption and FRE (the temporal integral of fire radiative power – FRP).

To calculate the $PM_{2.5}$ emissions for each of the identified burning points, the emission factors used were determined according to the method proposed by Zhang et al. (2011, 2012), and Li et al. (2019):

$$FRE = FRP \times 900 \times 8 \times 4 \tag{1}$$

where FRE is the fire radiative energy (MJ) released during the life of the fire in the burned area, FRP (MW) is the constancy of the fire within 15 min ("900" corresponds to the time in seconds), 8 corresponds to the estimated mean number of hours during, which the burning occurred, and 4 is the value of the factor that transforms minutes into an hour. A biomass burning period of 8 h was considered as the reference by Li et al. (2018), where 445 burning points were evaluated, as well as the type of vegetation and dry climate of the Colombian Caribbean, which promote biomass burning for long periods (especially in areas of difficult access within the Isla Salamanca mangrove park).

Subsequently, for the calculation of biomass consumption, the equation proposed by Wooster et al. (2005) and Yin et al. (2019) was used:

$$BB = FRE \times Cr \tag{2}$$

where BB is equivalent to biomass consumption (kg), FRE is the amount of particulate material released during the fire, and Cr (0.411 kg/MJ; Yin et al., 2019) is the conversion ratio used to convert FRE into burned biomass.

### 2.4. HYSPLIT dispersion model

To determine the contribution of biomass burning to $PM_{2.5}$ concentrations, the HYSPLIT dispersion model was used. In this case, the particles were treated, as an inert tracer without chemical interactions, with other atmospheric components, and without the occurrence of material deposition (Malamakal et al., 2013). To perform dispersion modeling, the biomass consumption (kg) at each of the burning points (obtained from Eq. 2) was considered to determine the emission of the atmospheric particulate material. The burning duration was considered to be 8 h, and the dispersion process corresponded to 24 h from the burning focus identified by the satellite. The contributions of emissions from each evaluated burning point to $PM_{2.5}$ concentrations were recorded every hour, during which time the dispersion plume extends beyond the monitoring sites. Finally, the contributions from every evaluated point were added for each municipality, and the daily average $PM_{2.5}$ contributions were calculated.

The concentrations obtained from the HYSPLIT dispersion model correspond only to the $PM_{2.5}$ fraction emitted by the biomass burning, and, therefore, it is possible to establish the contribution of this specific source to the total concentrations of $PM_{2.5}$.

## 3. Results and discussion

### 3.1. $PM_{2.5}$ emissions from biomass burning

Table 1 shows the results obtained with remote-sensing tools for 1089 burning points identified during the study period and the corresponding FRPs used to estimate the biomass consumption (emission factor). The daily average $PM_{2.5}$ concentrations registered at each monitoring station (field measured) and the respective concentrations of the BB contribution (modeled using the HYSPLIT dispersion model) are shown in Fig. 2.

For the period between February 24 and March 30, 2018, the average $PM_{2.5}$ concentrations for Soledad and Malambo were 19.91 ± 5.6 $\mu g/m^3$ and 22.44 ± 6.4 $\mu g/m^3$, respectively. In contrast, the contributions of the modeled BB were, on average, 22.8% and 28.8% of the $PM_{2.5}$ concentrations, respectively.

For Soledad, <25%, 25%–50%, 50%–75%, and > 100% (overestimation) of $PM_{2.5}$ concentrations were associated with the biomass burning during 19, 7, 2, and 2 days in the evaluation period, respectively. In contrast, for Malambo, <25%, 25%–50%, 50%–75%, 75%–100%, and >100% of $PM_{2.5}$ concentrations were associated with the biomass burning during 16, 5,

**Table 1**
Identification of the number of biomass burning events (# BBE) and the respective FRP (MW) values registered.

| Date | # BBE | Minimum FRP | Maximum FRP | Average FRP |
|---|---|---|---|---|
| 24/02/2018 | 9 | 15.7 | 45.9 | 26.5 |
| 25/02/2018 | 3 | 24.9 | 44 | 37.4 |
| 26/02/2018 | 17 | 5.9 | 87 | 26.8 |
| 27/02/2018 | 12 | 17.2 | 126.5 | 54.8 |
| 28/02/2018 | 37 | 5.9 | 110.3 | 22.8 |
| 01/03/2018 | 5 | 9 | 44 | 22 |
| 02/03/2018 | 62 | 5.3 | 116.5 | 20.6 |
| 03/03/2018 | 6 | 7.5 | 59.8 | 29.8 |
| 04/03/2018 | 6 | 12 | 86.3 | 33.9 |
| 05/03/2018 | 54 | 19.1 | 476.8 | 58.7 |
| 06/03/2018 | 13 | 15.5 | 240.4 | 65.6 |
| 07/03/2018 | 64 | 4.9 | 106.7 | 23.0 |
| 08/03/2018 | 0 | – | – | – |
| 09/03/2018 | 66 | 4.1 | 304.4 | 26.2 |
| 10/03/2018 | 9 | 39.3 | 139.6 | 75.2 |
| 11/03/2018 | 66 | 5.4 | 97.8 | 20.8 |
| 12/03/2018 | 35 | 4.5 | 244 | 77.0 |
| 13/03/2018 | 27 | 9 | 84.3 | 26.7 |
| 14/03/2018 | 38 | 7.9 | 58.8 | 27.7 |
| 15/03/2018 | 8 | 27.8 | 51.2 | 37.4 |
| 16/03/2018 | 42 | 7.4 | 39.7 | 16.3 |
| 17/03/2018 | 1 | 11 | 11 | 11 |
| 18/03/2018 | 39 | 4.8 | 79.2 | 17.2 |
| 19/03/2018 | 3 | 57 | 86.2 | 74.9 |
| 20/03/2018 | 151 | 8.2 | 416 | 31.4 |
| 21/03/2018 | 31 | 5.4 | 136.3 | 26.8 |
| 22/03/2018 | 13 | 20 | 63.5 | 34.5 |
| 23/03/2018 | 18 | 8.8 | 42.3 | 23.1 |
| 24/03/2018 | 20 | 24.4 | 245.5 | 71.9 |
| 25/03/2018 | 169 | 4 | 214.4 | 21.6 |
| 26/03/2018 | 4 | 6.5 | 33.8 | 21.4 |
| 27/03/2018 | 10 | 6.6 | 44.1 | 20.5 |
| 28/03/2018 | 11 | 14.4 | 95.3 | 36.0 |
| 29/03/2018 | 30 | 8.1 | 310.6 | 45.1 |
| 30/03/2018 | 10 | 7.4 | 68.2 | 20.6 |

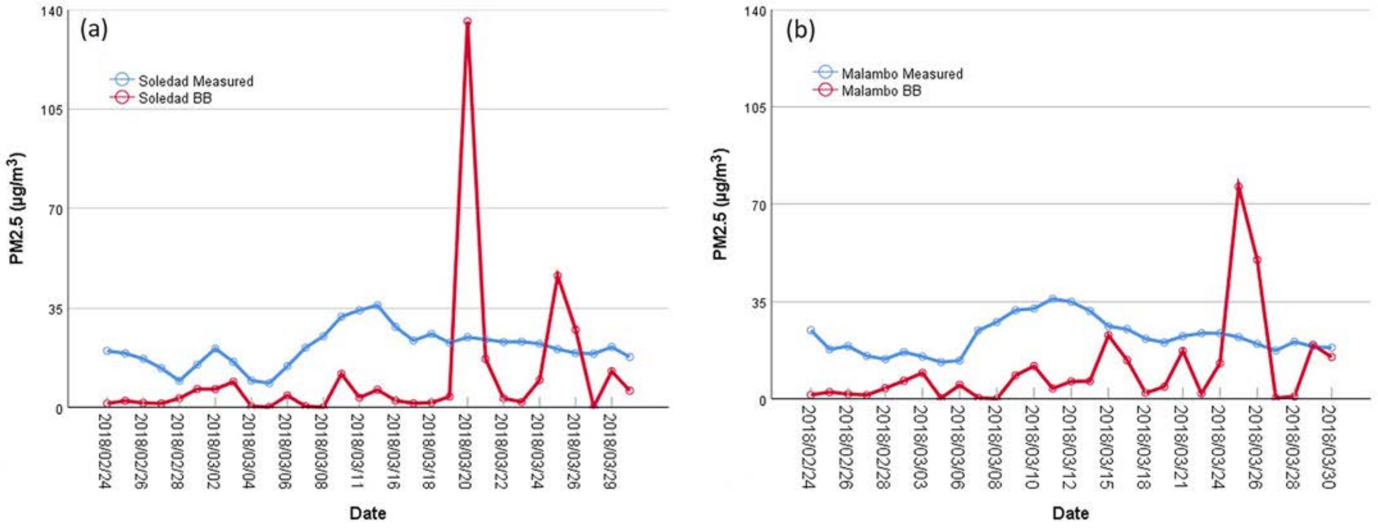

**Fig. 2.** Daily average $PM_{2.5}$ concentrations (field measured) and the respective contribution of biomass burning (modeled - by using the HYSPLIT dispersion model) for (a) Soledad and (b) Malambo.

3, 2, and 3 days, respectively. For days with an overestimation of the biomass burning contribution to $PM_{2.5}$ concentrations, a higher number of burning points were observed in the study area and surroundings, indicative of the accumulation of errors in certain evaluated burning points. In addition, as contributions from points located in different departments were evaluated for regional transport (Magdalena, Cesar and La Guajira, as can be observed in Fig. 1), the contribution of the burning points was frequently identified on the day after the day on which the burning was recorded. This finding agrees with the results of the study conducted by Wu et al. (2018), where the evaluated episodes spanned over several days and showed peaks of effects outside the trend with respect to days on which the burning episodes did not occur.

Certain cases of overestimation of the modeled contributions of biomass burning were detected (in terms of concentrations) when compared with the total concentration of $PM_{2.5}$ (March 20, 25, and 26, 2018). However, the dispersion model and methodology used in the present study suggested satisfactory results to obtain data indicative of the contribution of biomass burning. According to a similar study by Yin et al. (2019), the uncertainty of the results obtained for calculating the emissions can vary between 10% and 31%. The main sources of error that can impact the accuracy of estimations are associated with the radiative energy diurnal cycle parameterization that impacts the calculation of FRE; error in the fire detection and empirical formula for computing FRP; the use of the conversion ratio to convert FRE to combusted biomass, because emission factors vary in time and space (Vermote et al., 2009; Yin et al., 2019).

The results obtained in this study are in agreement with those of the studies in which sites located in urban and industrial areas in other parts of the world were evaluated. However, the contribution of biomass burning was less than 25% (Huang et al., 2014; Zhou et al., 2018; Islam

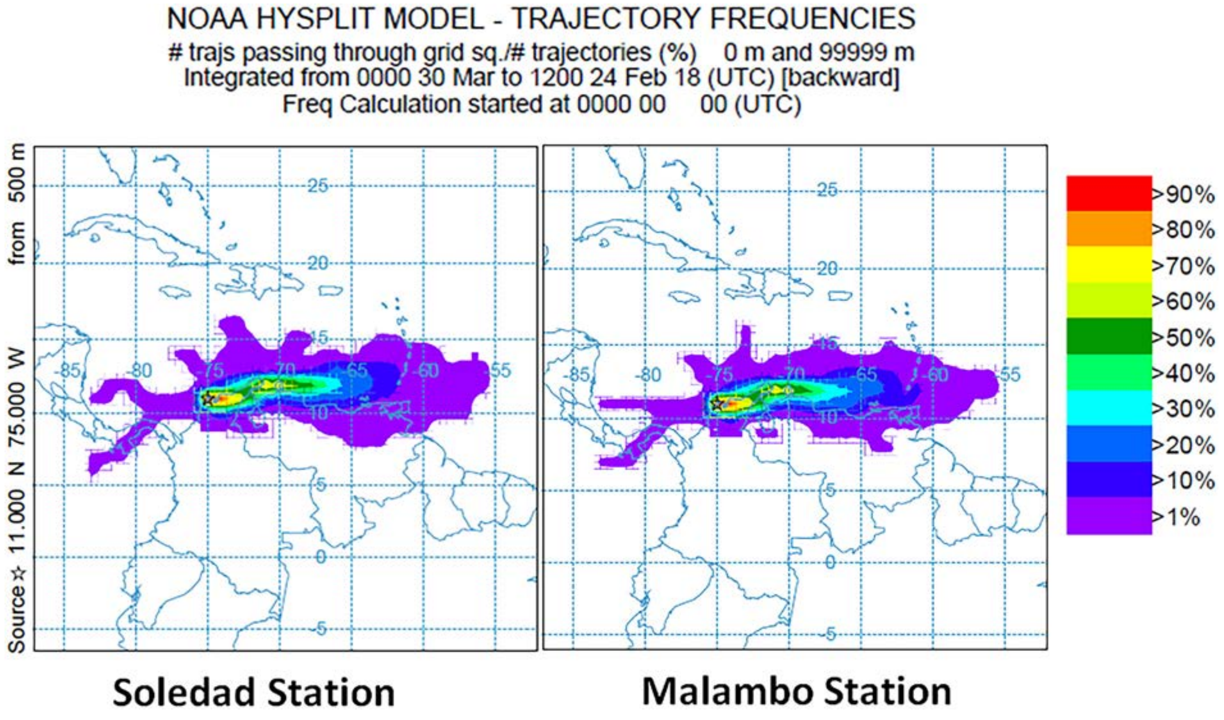

**Fig. 3.** Backward HYSPLIT trajectories corresponding to the study period for the evaluated stations.

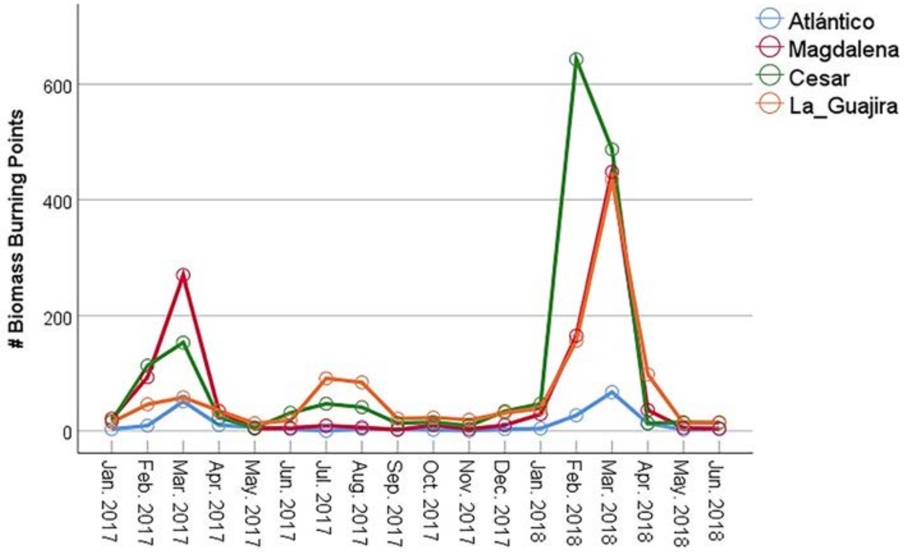

**Fig. 4.** Monthly biomass burning episodes by department of the Colombian Caribbean.

et al., 2019; Turap et al., 2019; She et al., 2020). In addition, on a few days, the contribution of burning was overestimated, primarily because predicting $PM_{2.5}$ in an urban scale was still prone to errors, and many aspects must be considered, such as the terrain resolution influences in topography scenarios, precise descriptions of surface wind flow (Guo et al., 2018), the size of the resolution used (Malamakal et al., 2013), meteorological variables, and high pollutants concentrations (Kota et al., 2018). Moreover, these interferences were observed in a previous study conducted by Noda et al. (2019) in eastern Europe. However, as the main objective of this study was to encourage the use of a practical methodology for obtaining the contribution of biomass burning using freely available tools, we did not focus on this work on solving these sources of error, which can vary in time and space and are considerably complex to be implemented (Figs. 3 and 4).

It is essential to note that although this study only evaluated the impact of biomass burning on $PM_{2.5}$ concentrations for periods in which these contributions were classified as significant, emissions associated with other urban and industrial sources also existed and could be significant. As can be seen from Supplementary Material, the selected study period was the one with the highest number of burning points recorded in the vicinity of the study area. Other significant anthropogenic sources of $PM_{2.5}$ were vehicle emissions, which, owing to the increasing demand for automobiles, tend to remain on the rise (Masiol et al., 2019; Silva et al., 2020c). To investigate the contributions of these sources, other methodologies must be used, including dispersion models and/or receptor models, which require chemical characterization of specific tracers from the sources.

### 3.2. Evaluation of the influence of regional transport

Table 2 presents Pearson's correlation coefficients between the number of burning points and the measured $PM_{2.5}$ concentrations, and the modeled contributions of biomass burning. A significant correlation existed between the burning points of all departments evaluated. This occurred because the dry period between February and March was characteristic of the entire Colombian Caribbean region. The most significant relationships were observed for the departments of Cesar and La Guajira, having a large number of burning points (227 and 466, respectively).

When the results for the effect of the number of burning points in Soledad and Malambo on $PM_{2.5}$ concentration modeling results were compared, a significant correlation was observed between the results for the two stations, with a higher influence observed for the Malambo station. However, in addition to the number of burning points, factors such as the duration and extension of the burning, season, meteorological conditions, and FRP (fire constancy) affected the emissions of atmospheric particulate matter (Hoyos et al., 2017), which should be considered.

An example of these effects can be observed when the correlations between the burning points in the Atlántico and Magdalena departments (closest to the evaluated stations) and the biomass contributions in Soledad and Malambo were compared. Although there was a positive relationship—that is, with an increasing number of burning points, the $PM_{2.5}$ concentrations increased—this effect was not significant (Table 2). In contrast, the burning points in Cesar and La Guajira departments, more distant from the evaluated municipalities, showed significant correlations with the biomass contribution of the two evaluated

**Table 2**
Correlation matrix between the number of biomass burning events (# BBE), the modeled biomass burning contribution (BBC), and the measured $PM_{2.5}$ concentrations ($PM_{2.5}$).

| | Total # BBE | # BBE Atlántico | # BBE Magdalena | # BBE Cesar | # BBE La Guajira | $PM_{2.5}$ Soledad | BBC Soledad | $PM_{2.5}$ Malambo | BBC Malambo |
|---|---|---|---|---|---|---|---|---|---|
| Total # BBE | 1 | 0.643** | 0.660** | 0.908** | 0.937** | 0.155 | 0.696** | 0.205 | 0.712** |
| # BBE Atlántico | | 1 | 0.108 | 0.754** | 0.513* | 0.015 | 0.183 | 0.001 | 0.321 |
| # BBE Magdalena | | | 1 | 0.464* | 0.411* | 0.338 | 0.263 | 0.447* | 0.211 |
| # BBE Cesar | | | | 1 | 0.794** | 0.125 | 0.543** | 0.065 | 0.590** |
| # BBE La Guajira | | | | | 1 | 0.098 | 0.866** | 0.105 | 0.889** |
| $PM_{2.5}$ Soledad | | | | | | 1 | 0.132 | 0.931** | 0.123 |
| BBC Soledad | | | | | | | 1 | 0.038 | 0.974** |
| $PM_{2.5}$ Malambo | | | | | | | | 1 | 0.014 |
| BBC Malambo | | | | | | | | | 1 |

** The correlation is significant at the 0.01 level.

* The correlation is significant at the 0.05 level.

stations. This occurred primarily due to the location of the burning points and the transport action of the winds. Considering that the prevailing wind came from the northeast, the effect of biomass burning on La Guajira (the department that is located further north in Colombia) was more significant, indicating the strong regional effect of fires on the concentrations of $PM_{2.5}$ registered in Soledad and Malambo. Similarly, the cumulative effect of concentrations of transported $PM_{2.5}$—that is, the sum of the contributions of biomass burning at the closest points with that at the most distant ones—could also be responsible for this effect.

## 4. Conclusions

Based on the criteria and analysis of results for the period between February 24 and March 30, 2018, the average contribution of biomass burning to $PM_{2.5}$ concentrations was calculated for the Soledad and Malambo monitoring stations, located in the Colombian Caribbean. Using the HYSPLIT dispersion model, through forwarding trajectories, an average contribution of 20%–30% was determined for these two municipalities. This is a significant influence, especially when considering urban and industrial areas, where sources such as vehicular traffic and industrial emissions also significantly impacted $PM_{2.5}$ concentrations. The tools used in the present study have been rarely used for the evaluation of the contribution of biomass burning to atmospheric pollutants. However, as can be verified, they present good results allowing a better understanding of the impact that burning had on the air quality of a given region. In addition, this method had a great advantage because it did not require knowledge of the burned area, fuel load, and combustion completeness, and the burn severity, because the emissions were calculated directly from the total emitted FRE. Therefore, this methodology should be used in places where there was little or no information regarding air quality. This will clarify the impact of biomass burning and $PM_{2.5}$ concentrations variation with time and space. In addition, it will help in making decisions about strategies to improve the air quality management plans and to mitigate the effects on human health.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.gsf.2021.101152.

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