MOVEIM v1.0: Development of a bottom-up motor vehicular emission inventories for the urban area of Manaus in central Amazon rainforest.

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Abstract. Emissions of gases and particulates in urban areas are associated with a mixture from various sources, both natural and anthropogenic. Understanding and quantifying these emissions is necessary in studies of climate change, local air pollution and weather modification issues. Studies have highlighted that the transport sector is key to closing the world's emissions gap. Vehicles contribute substantially to the emission of carbon dioxide (CO_2), carbon monoxide (CO), nitrogen oxides (NO_x), non-methane hydrocarbon (NMHC), particulate matter (PM), methane (CH_4), hydrofluorocarbon (HFC) and nitrous oxide (N_2O). Several studies show that vehicle emission inventories are an important approach for providing a baseline estimate of on-road emissions in several scales, mainly in urban areas. This approach is essential to areas with incomplete or non-existent monitoring networks as well as for air quality models. Conversely, the direct downscale of global emission inventories in chemical transport and air quality models may not be able to reproduce the observed evolution of atmospheric pollution processes at finer spatial scales. To address this caveat, we developed a bottom-up vehicular emission inventory along the 258 main traffic routes in Manaus, based on local vehicle fleet data and emission factors (EFs). The results showed that light vehicles are responsible for the largest fraction of the pollutants and contribute 2.6, 0.87, 0.32, 0.03, 456 and 0.8 ton/h of CO, NO_x, CH_4, PM, CO_2 and NMHC, respectively. Our total estimate of the emissions, including the emissions of motorcycles, buses and trucks, was 4.1, 1.0, 0.37, 0.07, 63.5 and 2.56 ton/h, respectively. We also noted that light vehicles account for about 62.8%, 84.7%, 87.9%, 45.1%, 71.8%, and 33.9% and motorcycles in the order of 32.3 %, 6.5 %, 12.1 %, 6.2 %, 14.8 %, 8.7 %, respectively. Nevertheless, we can highlight the bus emissions which are around 35.7% and 45.3 % for NMHC and PM. Our results indicate a better distribution over the domain reflecting the influences of standard behavior of traffic distribution per vehicle category. Finally, this inventory provides more detailed information which may help to improve the current understanding of how vehicle emissions contribute to the pollution concentrations in Manaus, and their impacts on regional climate change. This work will also contribute to the improvement of air quality numerical simulations, provide more accurate scenarios for policymakers and regulatory agencies when developing strategies for controlling vehicular emissions, and, consequently, mitigate associated impacts on local and regional scales of the Amazon ecosystems.

Key words: Vehicle emission inventories, bottom-up approach, urban air pollution, Amazon forest

1 Introduction

Since the pre-industrial era, climate change driven by anthropogenic emissions has become one of the most pressing challenges faced by society. Researchers have highlighted the effects of human activities on air quality, terrestrial ecosystems and global climate changes (Ramanathan et al. 2001; IPCC, 2014; Ashfold et al., 2015). The rapid economic and population growth, combined with a consequential increase in the number of vehicles, has contributed significantly to greenhouse gas (GHG) emissions and other pollutants, and, therefore, affect the climate on a global scale (Chapman, 2007; Stanley et al., 2011) besides causing adverse consequences to human health (Afroz et al., 2003; Abe et al., 2016; Scovronick et al., 2016; Yoshizaki et al., 2017). The GHG emissions associated with the transport sector have increased at a faster rate. Kahn et al. (2007) showed that, in 2004, the transport sector was responsible for 23% of the world's GHG emissions with about 75% coming from road vehicles. Recent studies suggested that, for the atmospheric emissions, the vehicle fleet is globally responsible for 30% of NO_x, 25% of PM2.5, 54% of CO and 14% of CO2 (Vasconcellos, 2006, Sokhi, 2011; Karangulian et al., 2015). Additionally, Sims et al (2014) showed that in 2010 the GHG emissions from the transport sector continued to increase at a faster rate than any other sector, with 7.0 Gt $CO_{2eq.}$ This means that the rate has more than doubled since 1970 (2.9 Gt CO_{2eq}). 53% of this increase is from passenger transport and 47% is from freight transport, totaling 5 Gt CO_{2eq}. The authors consider that more knowledge is needed on the worldwide potential for GHG emission reductions from the transport sector, and that potential reduction is much more certain for passenger modes. During the United Nations Conference of Parties 21 (UN COP21) Climate Change Conference, it was highlighted that the transportation sector is key to closing the world's emissions gap (Ebinger et al., 2015). The world's emissions gap represents the difference between the emissions levels that countries have pledged to achieve under the Paris Agreement to combat climate change. The main goal is to hold the increase in the global average temperature to below 2°C, when compared to pre-industrial levels and consistent with the global effect of the Intended Nationally Determined Contributions (INDCs) (Rogelj et al., 2016; UNEP, 2017).

However, an air pollution monitoring network in many urban areas is either unavailable or inadequate. Alves et al (2014) suggested that in Brazil only 1.7 % of the cities have an air pollution monitoring network, which represents 1.3 stations per 1 million inhabitants. These numbers are considerably lower than those in the U.S. (16 stations per 1 million inhabitants) and Europe (14.8 stations per 1 million inhabitants). Thus, vehicle emission inventories are a simple and much-needed approach that would provide a baseline estimate of on-road emissions on several scales. This information is essential for areas with incomplete or non-existent monitoring networks (Nagpure and Gurjar, 2012) and to constrain pollutants surface fluxes for numerical air quality models (Coelho et al., 2014; Lozhkina and Lozhkin, 2015; Vara-Vela et al., 2016). As a means of minimizing this gap in the monitoring network, some studies have suggested, in general, two different approaches: top-down and bottom-up. The top-down approach uses values of annual emissions assessed at national levels; these emissions are spatially disaggregated at different levels by statistical indexes (e.g. population density, average number of trips, etc.). However, the 'bottom-up' approach is more accurate and uses data at local and municipal levels (e.g., locally measured emission factors, vehicular activity, fuel consumption, traffic characteristics, fleet characteristics, length of road, etc.). In several studies, both methods are utilized for improving the accuracy of the emissions calculations by applying a downscaling of national emissions, therefore disaggregating atmospheric emissions from the national scale to a city-scale (Kuenen et al., 2014; Janssens-Maenhout et al., 2015; Trombetti et al., 2017). In addition, Dios et al. (2012) suggest combining top-down and bottom-up methodologies for high-resolution inventories. However, despite efforts, Zhou et al (2017) suggested that direct application of downscaled global emission inventories in chemical transport and air quality models may not be a good solution for reproducing the real evolution of atmospheric pollution processes at smaller spatial scales, becausethe application of downscaling produces emission overestimates.

Recent efforts have been made to develop vehicle emission inventories for several urban areas (Song et al., 2006; Bellasio et al., 2007; Jing et al., 2016; Andrade et al., 2010; Alonso et al., 2010; Venegas et al., 2011; Zhou et al., 2014). A few years ago, in South America, a number of studies reported information on vehicle emission inventories on a national scale or for specific cities. Gallardo et al. (2012) presented an evaluation of vehicle emission inventories for CO and NO_x in Bogotá (Colombia), Buenos Aires (Argentina), Santiago (Chile) and São Paulo (Brazil). Puliafito et al. (2017), Puliafito et al. (2015), Venegas et al. (2011) suggested a spatial disaggregated emission inventory in high resolution for Argentina. Alonso et al. (2010) developed an urban emissions inventory for South America based on the analysis and aggregation of local inventories of nine megacities by using socio-economic data from the region and correlation between vehicle density and mobile source emissions. This information was extrapolated geographically and distributed using a methodology that delimits urban areas by using high-resolution satellite data and was then integrated into worldwide emissions databases. In Brazil, several studies reported information on vehicle emission inventories in specific cities, such as Brasilia-Federal District (Réquia Júnior et al., 2015); Rio de Janeiro (Duarte et al., 2013); São Paulo (Andrade et al., 2004; Vivanco and Andrade, 2006; Martins et al., 2006; Gallardo et al., 2012); Campinas (Ueda and Tomaz, 2011). However, despite the efforts to implement an air pollution monitoring network on a national scale in the North, Northeast and Midwest regions of Brazil, there are still no emission-specific inventories at local and municipal levels.

In Brazil, in the Northern Region and located in middle of the world's largest rainforest, is the city of Manaus, which stands out for being a large urban area surrounded by primary tropical forests (Martin et al., 2016; Cecchini et al., 2016). Given such an environment, it is paramount to study the impact that Manaus has on atmospheric conditions. Studies have shown that the Amazon rainforest is sensitive to the variability and changes in the climate system due to both natural variations and anthropogenic actions, such as the increase in the concentration of GHG and aerosols in the atmosphere and changes in land use and land cover (LULC) (Fearnside et al., 2002; Artaxo et al., 2006; Betts et al., 2008; de Souza e Alvalá, 2014; Marengo e Espinoza, 2015). Previous studies of emissions have shown the effects of anthropogenic impact on the Amazon basin generally focused on biomass burning-related occasions (Artaxo et al., 2002; Roberts et al., 2003; Andreae et al., 2004; Freud et al., 2008; Martins and Silva Dias, 2009; Artaxo et al., 2013). However, over the last years, several researchers have highlighted the effects of the Manaus plume pollution on the chemical properties of the local and remote atmosphere (Kuhn et al., 2010; Trebs et al., 2012; Rizzo et al., 2013; Bateman et al., 2017). During 2014-2015, the experiment named Observations and Modeling of the Green Ocean Amazon (GoAmazon2014/5) was performed in the metropolitan area of Manaus, the objective was to understand and quantify the impact of the pollution plume from the urban area of Manaus on the complex interactions among vegetation, atmospheric chemistry, and aerosol production, as well as their connections to aerosols, clouds, and precipitation (Martin et al., 2016). As part of the GoAmazon 2014/5 Experiment, the most recent results indicate that Manaus's pollution plume impacts on the microphysical properties (e.g., smaller effective diameters and higher droplet number concentrations) of warm-phase clouds during the wet season (e.g., Cecchini et al., 2016). In addition, de Sá et al. (2017) suggested that urban pollution is responsible for the increased emissions of nitrogen oxides and decreased particulate matter (PM) compared to background conditions in the Amazon rainforest. The authors indicate that these results corroborate with some future scenarios of Amazonian economic development. In this context, the possible change in PM production would cause alterations in air quality and regional climate.

Therefore, given such an environment, it is essential to quantify sources of mobile emissions in Manaus. Specifically, the purpose of this paper is to develop a vehicular emission inventory along the main traffic routes which will be based on vehicle activity data and local emissions factors using a bottom-up methodology.

2 Methodology and data

2.1 Brief description of the study area

Manaus is situated at the confluence of the Negro and Solimões Rivers, more precisely between parallels 2°55'00" and 3°10'00" south and the meridians 59°52'30" and 60°07'30" west, occupying a total area of 377 km² (Figure 1). With a population of more than 2 million, it is the 7th most populous city in Brazil (IBGE, 2015) and responsible for about 80% of the economic activity in the state of Amazonas. Manaus has seen a rapid increase in its vehicle fleet and this is considered one of the major sources of air pollution; during 2010-2016, the average growth rate has been in the order of 7%. The motor vehicle census data from the National Transit Department (DENATRAN) show that in 2010 there were around 453,000 vehicles registered in Manaus. Today, the total is estimated at around 713,000 vehicles (78.6 % of total of the vehicles in the state of Amazonas), which indicates a 57.6% increase. At an annual growth rate of 7%, by 2020 the vehicle fleet could reach 1 million. The fleet in Manaus is relatively young in age and predominantly consists of flexible-fuel vehicles (blend between gasohol and hydrated ethanol); Medeiros et al. (2017) suggested an average age of 5 years attributed to the timing of rapid urban growth during the economic expansion between 2009 and 2015.

Climatologically speaking, in Manaus the mean air temperature does not show strong seasonal variations due to the high incidence of solar radiation throughout the year. The highest temperatures are observed during the dry season, with a September monthly mean of 27.5°C, whereas the lowest temperatures prevail in the rainy season, with a monthly mean of 25.9°C in March. Rainfall in the region shows a pronounced seasonal variation, with the highest amounts in March (335.4 mm) and the lowest amounts in August (47.3 mm), with an average annual total of 2307.4 mm (Andreae et al. 2015). A typical characteristic for the central Amazon Basin is the synoptic changes between the wet and dry seasons; a good example of this is in the seasonal variations of the IntraTropical Convergence Zone (ITCZ) (Fisch et al., 1998; Wang and Fu 2007; Nobre et al., 2009). In the wet season, the Manaus plume aside, the Amazon basin is one of the cleanest continental regions on Earth (Andreae, 2007; Martin et al., 2010). In general, the preferential wind direction is from the Northeast (NE), and features the occurrence of the breeze circulation in the same direction as the trade winds. Santos et al. (2014) observed that during the wet season, the trade winds flow more frequently from the Northeast (NE), while in the dry season they flow from the Southeast (SE). It has been suggested that these features are modulated by a land breeze circulation that is induced by the thermal gradient between Manaus and the surface of the river.

2.2 General methodology description

In this study, we applied a bottom-up approach in order to develop a vehicular emission inventory for the main anthropogenic emissions of an urban area: carbon monoxide (CO), nitrogen oxide (NO_x), methane (CH_4), particulate matter (PM), carbon dioxide (CO_2) and non-methane hydrocarbon (NMHC). Thus, for each segment of road, we established an hourly traffic profile for each vehicle category. The emissions were calculated as follows in Eq. (1):

$$E_{i,j}^{p} = \sum_{c} EF_{c}^{p} \times VTK_{c,i,j} \times 10^{-3} \qquad (1),$$

where $E_{i,j}^{p}$ is the emitted mass of a pollutant p on a segment of road i at time j (kg h^{-1}); EF_{c}^{p} is the emission factor of pollutant p by a vehicle category c (g km^{-1}); $VTK_{c,i,j}$ is distance travelled of a vehicle category c on a segment of road i at time j (km h^{-1}).

Due to the significant differences among different vehicle classifications, the emission factors were separated by the vehicle category. However, it was not possible to determine the exact age and fuel type of vehicle on a segment of road i at the moment of j. Thus, we used the existing classification method established by the Brazilian Ministry of Environment by which the vehicles have been summarized into 4 classes as follows: light vehicle - LV (e.g., passenger car, taxi); motorcycle; public transportation bus, and heavy goods vehicle - HDV (e.g., truck). The grouping intends to reflect the different fuels used and fleet-based functions for private and public transport, or transport of goods.

The method used to calculate VKT at the given time j for a segment of road i is to multiply the length of a road segment (L_i) by the volume of traffic of category c on that segment i at a given time j, as shown by Eq. (2):

$$VTK_{c,i,j} = VT_{c,i,j} \times L_i \qquad (2).$$

It is important to note that the VKT calculation does not include travel on all roads in Manaus. Small residential streets are not used in the VKT calculation; the traffic volume varies or the traffic count sample on these roadways is too small or frequently inexistent to make a reliable estimate.

2.2 Traffic flow, vehicle activity, vehicle density and emission factors

The fleet composition, vehicle activity, density and traffic flow were obtained from three local sources: The Amazonas state Transit Department (Detran-AM); the Manaus Municipal Institute of Engineering and Traffic Control (MIETCM) and the Municipal Institute of Urban Planning. For the traffic volume, a database from the MIETCM was used, and **we obtained data by manually counting vehicles along the 258 main traffic routes from Manaus, representing 85% of the roads likely to have high emission contribution, over two time** periods: morning rush hour (6–9 AM) and afternoon rush hour (5–7 PM). The counting was done over several days on each road between the years 2014-2015. Thus, for every selected road, the vehicle flow was continuously counted in 15-minute intervals during these two-hour periods. **In most Brazilian cities, the traffic volume is monitored only during the peak hours, furthermore in Manaus urban area the traffic volume doesn't show strong variations during the day-time. Thus, the off-peak periods is not considered in this study.**

The accuracy of the emission factors (EFs) is fundamental and affects the results of the vehicle emissions inventories. International EFs are hard to match perfectly since they are directly related to characteristics such as vehicle emission control level, fuel type, vehicle age, accumulated mileage, inspection and maintenance, average speed, fraction of cold/hot starts, etc. Some studies have quantified EFs by employing tunnel measurements (Martins et al., 2006; Ban-Weiss et al., 2010) or the remote sensing approach (Bishop et al., 2010). Despite the efforts to improve EFs, both of these approaches have significant limitations. Hudda et al. (2013) summarizes that tunnel measurements cannot provide variability showing only a central tendency. In contrast, remote sensing only allows for determining an individual vehicle's EF unless large numbers of locations are sampled in a representative manner. Therefore, in this research, we used the emission factors suggested by Cancelli and Dias (2014) which were based on data from the Environmental Agency of São Paulo (CETESB) and the first National Atmospheric Emissions from the Road Vehicles Inventory developed by the Brazilian Ministry of the Environment (MMA, 2011), which were determined for Brazilian vehicles (Table 1).

2.3 Spatial Evaluation

To spatial distribution was been compared with values of Emission Database for Global Atmospheric Research harmonized (EDGAR-HTAP, http://edgar.jrc.ec.europa.eu/htap, Janssens-Maenhout et al., 2012); REanalysis of the TROpospheric chemical composition over the past 40 years (RETRO, http://retro.enes.org) and the urban emissions inventory for South America (Alonso et al, 2010). Thus, version 1.5 of the PREP-CHEM-SRC system (ftp://ftp.cptec.inpe.br/brams/PREP-CHEM/PREP-CHEM-SRC-1.5.tar.gz) was utilized to standardize the emission inventories at a 1km horizontal resolution. PREP-CHEM-SRC is a comprehensive tool that aims to prepare emission fields of trace gases and aerosols for use in atmospheric-chemistry transport models (Freitas et al., 2011).

3 Results and discussion

This section introduces our bottom-up vehicle emission inventory for the Manaus urban area, which resulted from applying the methodology described above and locally collected data and information. Traffic density has been intensively monitored for a number of years in the Manaus urban area, however, we only considered the data for years 2014 and 2015. Figure 2 shows the traffic density for light vehicles, motorcycles, buses and trucks,for the 258 roads which were analysed. The thickness of the line on the map relates to the amount of traffic. The map indicates a preferential direction of light vehicles, bus and trucks, while motorcycles show a more homogenous distribution.

Table 2 shows a statistical summary of vehicle emissions from different categories over the study area. The totals of emissions are 4.1, 1.0, 0.37, 0.072, 63.5 and 2.56 ton/h for CO, NO_x, CH_4, PM, CO_2 and NMHC, respectively. From these totals the light vehicles are responsible for a large proportion of the pollutants, and contribute 2.6, 0.87, 0.32, 0.03, 456 and 0.8 tons/h.

We noted that light vehicles represent about ~62.8 %, 84.7 %, 87.9 %, 45.1 %, 71.8 %, and 33.9 % and motorcycles in the order of 32.28 %, 6.54 %, 12.06 %, 6.19 %, 14.77 %, and 8.71 %. Nevertheless, we can highlight the bus emissions which are around ~35.74% and 45.27% for NMHC and PM, respectively (Table 3). Réquia Junior et al (2015) found light vehicle emissions values in Brasilia - Brazil to be equal to 68.9 % of CO, 93.6 % of CH4 and 57.9 % of CO2, and for heavy vehicles (bus and trucks) observed values were in the order of 92.9 % and 97.4 % for NHMC and PM, respectively. In a recent study by Silva et al. (2016) which was conducted in Pelotas, Brazil, results suggested that light vehicles and motorcycles contribute ~63 % and 28 % of CO, respectively, while light vehicles, heavy vehicles (bus and trucks) and motorcycles contribute 72 % of NMHC, 76 % of NO_x and 18 % of NMHC. Duarte et al. (2013) suggested that light vehicles in Rio de Janeiro, Brazil, contribute 60 % of CO, 17 of NO_x and 2.9 of PM, while motorcycles and heavy vehicles emit 90 % and 5.9 %, respectively. In addition, Ueda and Tomaz (2011), using information from Campinas, Brazil, showed that light vehicles are responsible for 74 % of CO, while 61 % of NO_x and 99.9 % of PM are associated with heavy vehicles.

Figures 3 and 4 show the spatial distributions from the emission inventories of CO and NO_x for four vehicle categories. Although the spatial distribution trends of the pollutants' emissions are similar, there are some differences between categories of vehicles. Analyses of the distribution of emissions show that they are mostly higher in central zones due to the high traffic rate of passenger cars, motorcycles, buses and trucks. This pattern was observed in the results shown in Figure 2. It is worth noting that trucks are not allowed to enter residential areas, which leads to a considerable level of truck-related emissions on suburban roads around Manaus and in industrial areas.

To evaluate uncertainty in the spatial distribution and total emission in the urban area of Manaus, we compared the inventory proposed here (Local inventory - LI) with values of EDGAR-HTAP, RETRO and Alonso et al (2010). Despite the efforts to improve the level of detail, significant uncertainties still remain because different approaches are adopted for different spatial disaggregation methods, different resolutions, different criteria and others. For the urban area of Manaus Alonso et al (2010) suggested CO and NO_x values of 23.93 and 10.16 Gg year^{-1}, respectively. In contrast, the present results show values of CO and NO_x around 67.34 and 32.86 Gg year^{-1}. In general, for the study area, all databases that were utilized underestimated the total emissions of CO and NO_x emissions presented in LI by a factor of ~3. Similar results were found by Abdallah et al. (2016) for Lebanon-Middle East. The comparison of EDGAR-HTAP, RETRO and Alonso et al. (2010) over Manaus highlights the discrepancies between the inventories, both in terms of total mass and in spatial distribution. In LI emissions we show a better distribution over the domain, highlighting major urban roads (Figure 5). The differences between the totals and the spatial distribution may be related to the methods applied, but also they have a direct relationship with the size of the urban area and number of vehicles considered in the stIdies. For example, for Manaus, Alonso et al. (2010) utilized an area of ~265.32 km^2 and a total of around 581,000 vehicles. in contrast, for the inventory proposed here, we used an area of ~447 km^2 and a total of around 622,000 vehicles.

4 Conclusion

This paper introduces a detailed bottom-up vehicular emission inventory developed for Manaus, the capital of the Amazonas state (Brazil), based on local information and on the city scale. The estimated mobile emissions of CO, NO_x, CH_4, PM, CO_2 and NMHC are approximately 4.1, 1.0, 0.37, 0.072, 63.5 and 2.56 ton/h, respectively. In agreement with previous studies over different regions, light vehicles are mainly responsible for the total emissions, and account for approximately 62.8 %, 84.7 %, 87.9 %, 45.1 %, 71.8 %, and 33.9 % of the respective total mass of the above pollutants. Motorcycles come in second place producing with 32.3%, 6.5%, 12.1%, 6.2%, 14.8%, and 8.7% of the total mass. However, we can highlight the bus emissions which are ~35.74% and 45.27% for NMHC and PM, respectively. Our results indicate that the developed inventory reflects the influences of standard behavior of traffic distribution per vehicle category and better distribution over the domain. Furthermore, this inventory provides more accurate information which will improve the current understanding on how vehicle emissions contribute to the ambient pollutant concentrations, the direct and indirect impacts on regional climate changes and provides more detailed scenarios for policymakers and regulatory agencies in order to develop strategies for controlling vehicular emissions and, consequently, mitigate associated impacts on local and regional scales of the Amazon ecosystems.

Code and data availability

Most of the parts that comprise this methodology are publically available. The source code of PREP-CHEM-SRC is maintained and developed by the National Institute of Space Research, Center for Weather Forecasting and Climate Research by the GMAI group (Group Modeling of the Atmosphere and its Interfaces). The code and most of the global and South American emission database are available upon request to the 2nd author or can be downloaded from the ftp://ftp.cptec.inpe.br/brams/PREP-CHEM/PREP-CHEM-SRC-1.5.tar.gz. The new inventory and source code are currently being implemented within the PREP-CHEM-SRC, researchers will be able to access its code and database used in this study, as well as more recent versions, available upon request at no cost, via repository in https://doi.org/10.5281/zenodo.1245811. In addition, researcher interested in the new motor vehicle emission inventory for Manaus urban area and source code is encouraged to contact the corresponding author.

Acknowledgments

This work is part of the PhD thesis of the first author that is under development at the Post-Graduate Program in Climate and Environment (PPG-CLIAMB) of the National Research Institute of the Amazon (INPA) and the Amazonas State University (UEA) with financial support from Coordination for the Improvement of Higher Education Personnel (CAPES). We acknowledge the support of the Central Office of the Large-Scale Biosphere Atmosphere Experiment in Amazonia (LBA), the National Institute of Research of Amazônia (INPA), National Institute of Space Research (INPE), Center for Weather Forecasting and Climate Research (CPTEC) and the Amazonas State University. We also thank Group Modeling of the Atmosphere and its Interfaces (GMAI) - CPTEC. The first author thanks the CAPES for the grant scholarship, linked to PPG-CLIAMB. Thanks also go to Amy Houghton for their very valuable comments to improve this work.

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Figure 1. Area of study. Left map represents the metropolitan region of Manaus (areas in green represent forest cover and dark lines are the municipal boundaries; area in red represents deforestation accumulated until March 2014). The map in the upper-right corner shows urban area of Manaus'. The black lines represent the main roads, and grey lines are small roads.

Table 1. Emission factors (g km^{-1}) for the total number of vehicles per category (Cancelli and Dias, 2014).

	light vehicles	motorcycles	bus	trucks
CO	1.2	3	1.1	1
NO_x	0.4	0.15	0.5	0.4
CH_4	0.15	0.1	0	0
MP	0.015	0.01	0.2	0.15
CO_2	210	210	445	445
NMHC	0.4	0.5	9	5

Table 2. Descriptive statistics for pollutant vehicle emission (kg /h) of total number of vehicles per category for the urban area of Manaus, comprising of 258 roads.

		CO	NO_x	CH_4	PM	CO_2	NMHC
light vehicles	Average	10.108	3.369	1.263	0.126	1768.815	3.369
	standard deviation	16.006	5.335	2.001	0.200	2801.024	5.335
	variation coefficient	1.584	1.584	1.584	1.584	1.584	1.584
	Minimum	0.138	0.046	0.017	0.002	24.234	0.046
	Maximum	151.006	50.335	18.876	1.888	26426.006	50.335
	Total	2607.739	869.246	325.967	32.597	456354.276	869.246
		CO	NO_x	CH_4	PM	CO_2	NMHC
Motorcycles	Average	5.196	0.260	0.173	0.017	363.714	0.866
	standard deviation	7.554	0.378	0.252	0.025	528.754	1.259
	variation coefficient	1.454	1.454	1.454	1.454	1.454	1.454
	Minimum	0.063	0.003	0.002	0.000	4.406	0.010
	Maximum	55.247	2.762	1.842	0.184	3867.309	9.208
	Total	1340.545	67.027	44.685	4.468	93838.161	223.424
		CO	NO_x	CH_4	PM	CO_2	NMHC
Bus	Average	0.550	0.250	*	0.100	222.525	4.501
	standard deviation	0.917	0.417	*	0.167	371.092	7.505
	variation coefficient	1.668	1.668	*	1.668	1.668	1.668
	Minimum	0.008	0.004	*	0.001	3.175	0.064
	Maximum	8.359	3.800	*	1.520	3381.649	68.393
	Total	141.916	64.507	*	25.803	57411.443	1161.130
		CO	NO_x	CH_4	PM	CO_2	NMHC
Trucks	Average	0.241	0.096	*	0.036	107.284	1.205
	standard deviation	0.484	0.194	*	0.073	215.360	2.420
	variation coefficient	2.007	2.007	*	2.016	2.007	2.007
	Minimum	0.002	0.001	*	0.000	0.809	0.009
	Maximum	5.616	2.246	*	0.842	2498.939	28.078
	Total	62.201	24.880	*	9.330	27679.313	311.004

Note: * not calculated

Table 3. Summary of the contributions, in percentages, from air pollutant emission for each vehicle type, for urban area of Manaus, comprising of 258 roads.

Vehicle category	CO (%)	NO_x (%)	CH_4 (%)	PM (%)	CO_2 (%)	NMHC (%)
light vehicles	62.80	84.75	87.94	45.15	71.83	33.89
Motorcycles	32.28	6.54	12.06	6.19	14.77	8.71
Bus	3.42	6.29	*	35.74	9.04	45.27
Trucks	1.50	2.43	*	12.92	4.36	12.13
Total	100	100	100	100	100	100

Note: * not calculated

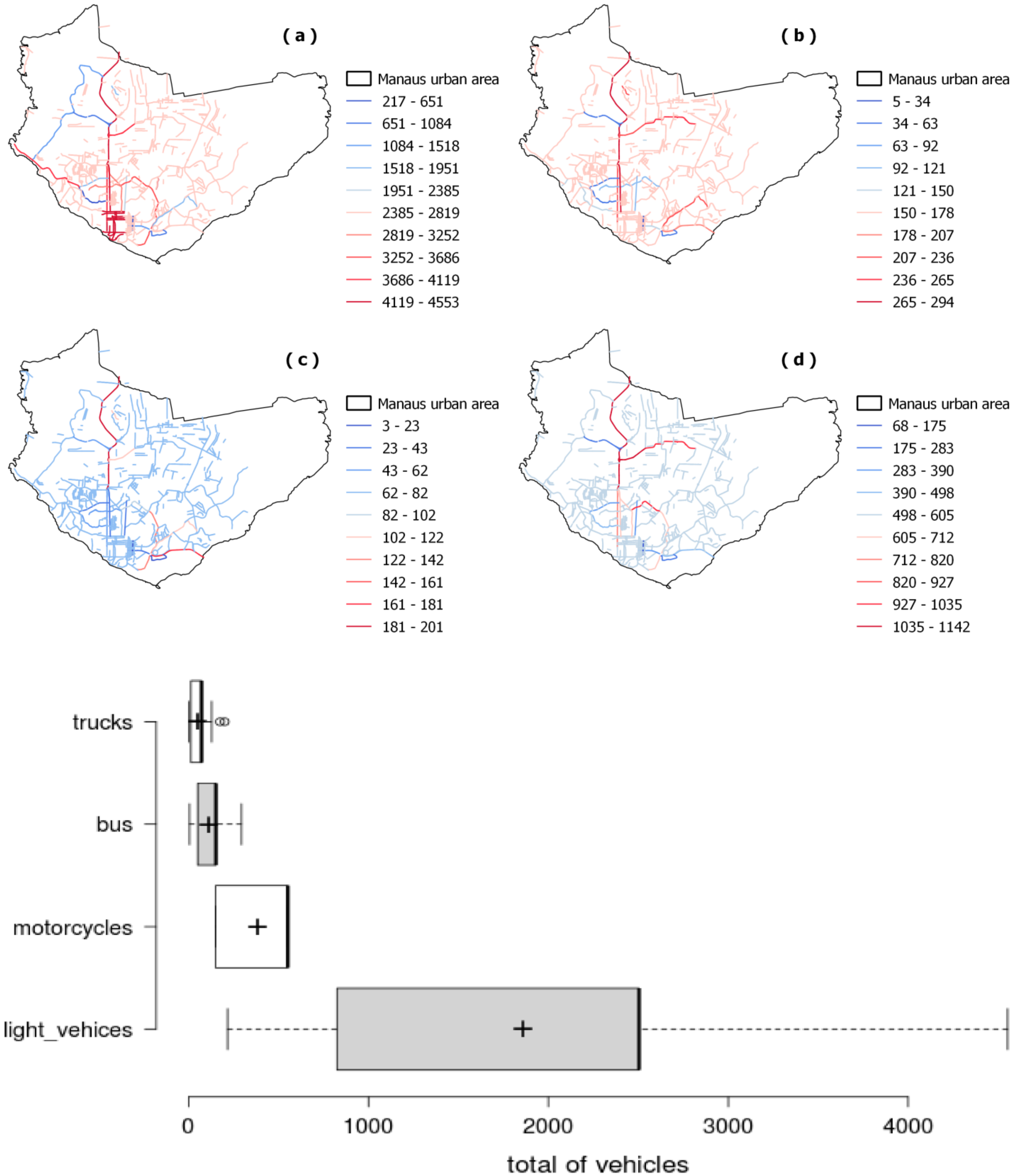

Figure 2. The top panel shows the mean spatial distribution of traffic density (vehicles/hr) along Manaus urban area main roads for each vehicle category, respectively: light vehicles (a); bus (b); trucks (c); motorcycles (d). The bottom panel shows the boxplot for each vehicle category. Upper and lower whiskers represent 1.5 interquartile ranges for the period, from the 25th and 75th percentiles; outliers are represented by dots. The crosses represent sample median value and the black square is the average value.

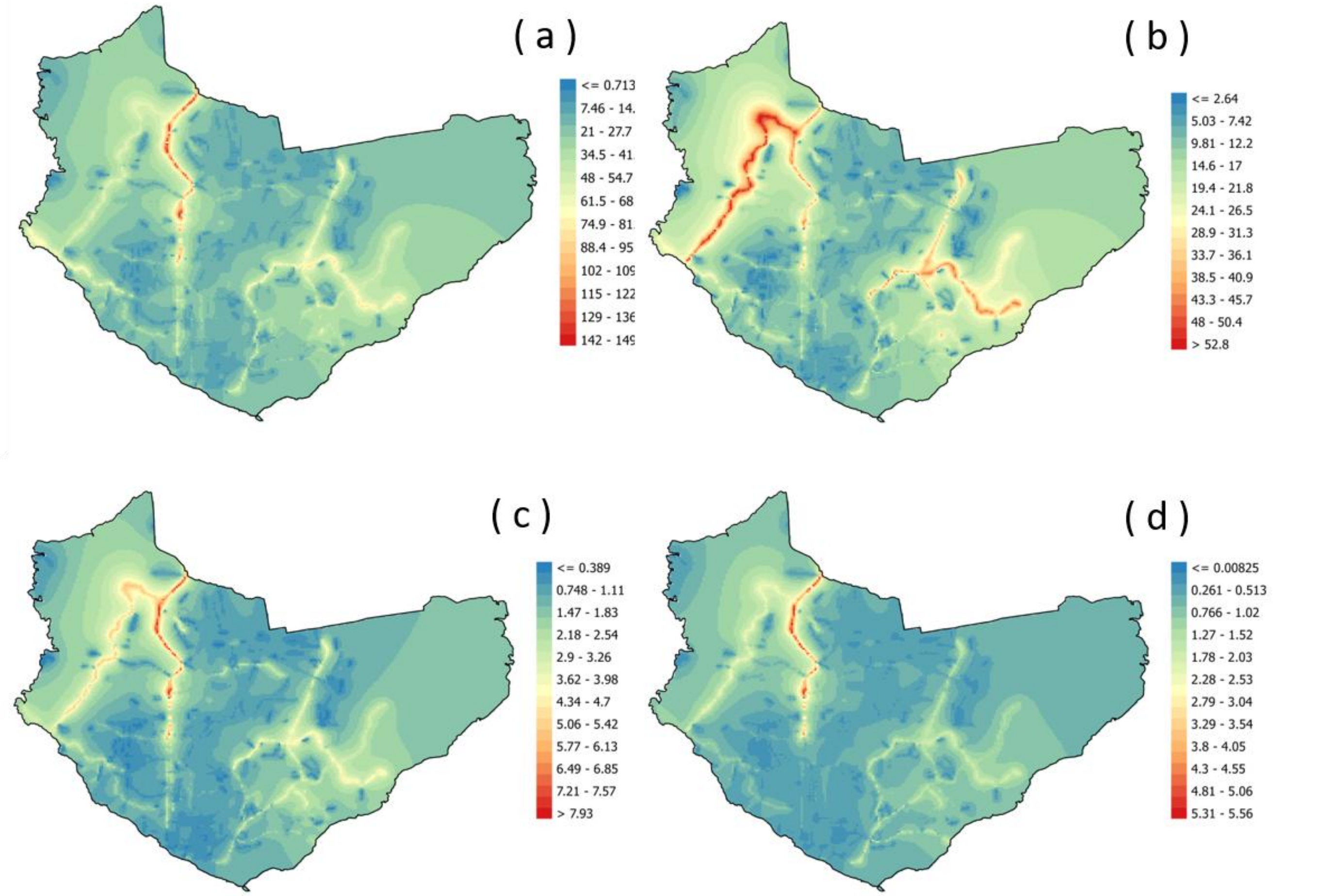

Figure 3. Grid-based vehicle emission inventory of CO at Manaus urban area for each vehicle category in kg h^{-1} , respectively: light vehicles (a); motorcycles (b); bus (c); trucks (d).

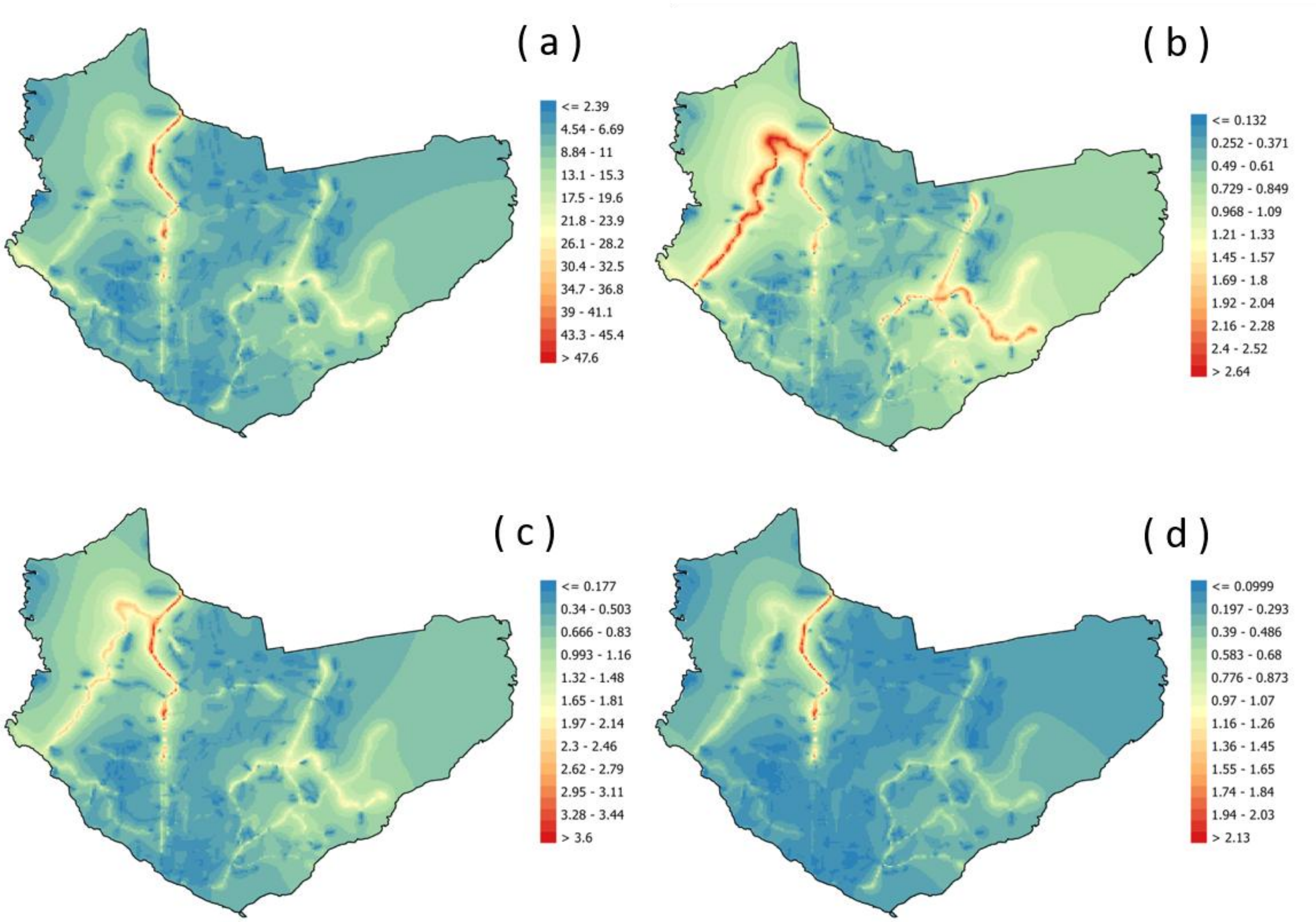

Figure 4. Grid-based vehicle emission inventory of NO_x at Manaus urban area for each vehicle category in kg h^{-1} , respectively: light vehicles (a); motorcycles (b); bus (c); trucks (d).

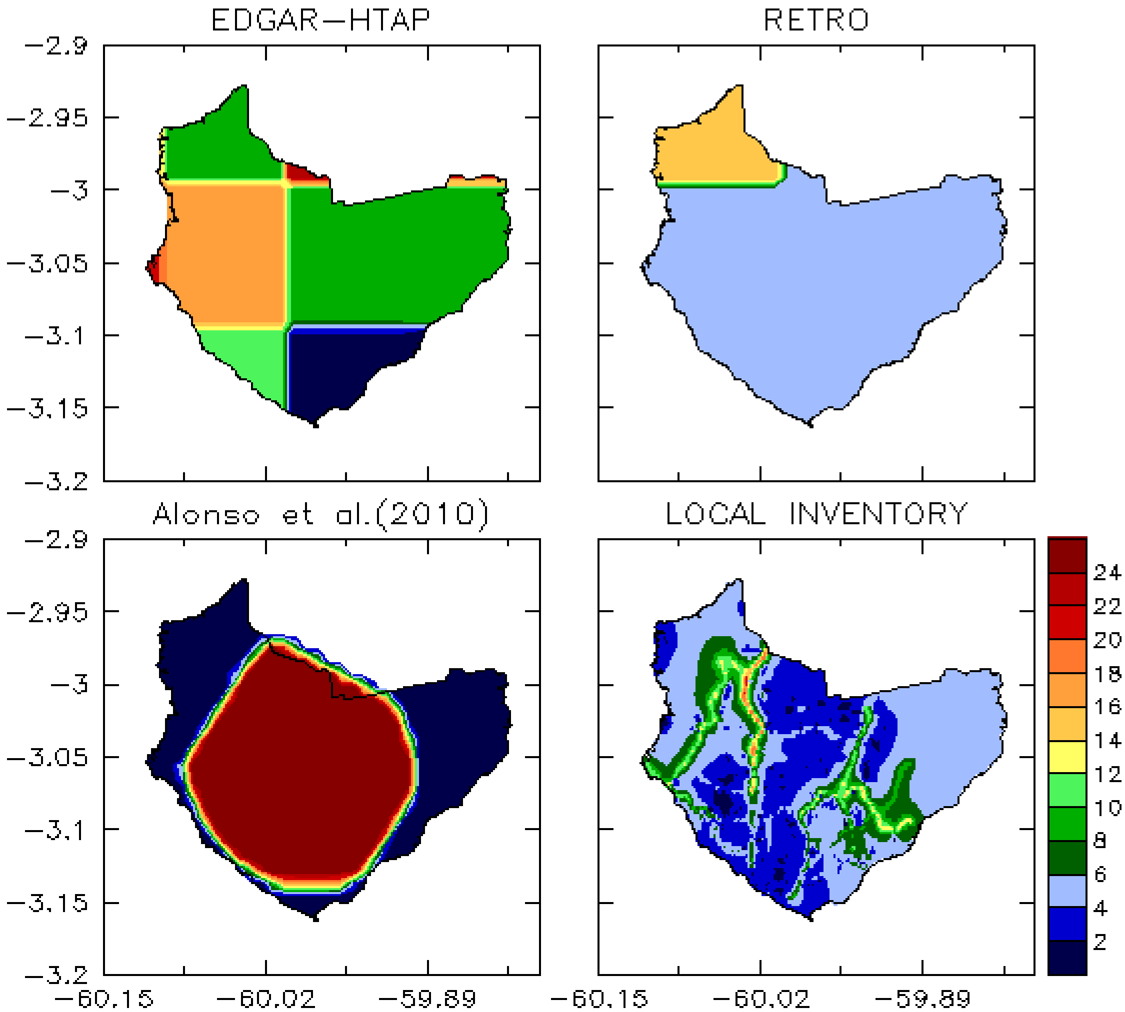

Figure 5. Spatial distribution of CO (10^{-6} kg m^{-2} day^{-1}) in the urban area of Manaus.