

Emissions and impact on air quality of particulate matter and black carbon in Curitiba, Paraná, Brazil

- diagnostic study of current situation (phase 1)

report elaborated¹ by

Prefeitura de Curitiba (ARIN, SMMA, IPPUC, URBS and others)

Universidade Federal do Paraná

Universidade Tecnológica Federal do Paraná

Universidade Federal de Pelotas

Departamento de Trânsito do Estado do Paraná

Instituto Ambiental do Paraná

Sistema Meteorológico do Paraná

Swedish Meteorological and Hydrological Institute

February 14, 2018

¹ Institutions contributing with data and texts to this specific report

CONTENT

CONTENT	2
1 EXECUTIVE SUMMARY.....	3
2 INTRODUCTION	8
2.1 PROJECT BACKGROUND	8
2.2 CURITIBA CITY.....	11
3 METHODS.....	15
3.1 EXPERIMENTAL DESIGN	15
3.2 METEOROLOGICAL INFORMATION	16
3.3 AIR QUALITY MONITORING	16
3.4 EMISSION INVENTORY	24
3.5 REGIONAL DISPERSION MODELING	30
3.6 LOCAL DISPERSION MODELING	33
4 RESULTS	36
4.1 METEOROLOGICAL CONDITIONS IN CURITIBA	36
4.2 AIR QUALITY MONITORING RESULTS.....	38
4.3 REGIONAL MODELING OF LONG-RANGE TRANSPORTED PM AND BC.....	48
4.4 LOCAL DISPERSION MODELING AND INTEGRATED ANALYSIS.....	51
4.5 OVERVIEW OF PRESENT AIR QUALITY LEVELS IN CURITIBA, IN COMPARISON TO EU AIR QUALITY DIRECTIVE AND WHO RECOMMENDATIONS	69
5 CONCLUSIONS	73
6 SUGGESTIONS FOR FUTURE WORK.....	74
7 ACKNOWLEDGEMENTS.....	75
8 REFERENCES	76

APPENDIX 1: PARCUR CONSORTIUM AND CONTACT PERSONS

APPENDIX 2: DETAILS OF MONITOR STATIONS DURING THE CAMPAIGN JULY-AUGUST 2016

Authors to this report:

- Lars Gidhagen, Jorge H. Amorim and David Segersson (SMHI)
- Francisco Mendonça, Ricardo Godoi, Francisco Castelhana, Gabriela Polezer (UFPR)
- Francisco Malucelli (IPPUC), Alyson Wolf (URBS), Guilherme Esquivel (SMMA)
- Dirlene Silva (IAP), Juçara Rieiro (DETRANPR)
- Patricia Krecl, Admir Targino, Erika Felix (UTFPR)
- Marcelo Alonso (UFPEL)

1 Executive summary

The city of Curitiba has gained worldwide prominence for its efficient practices in urban planning and public transport. Engaged in projects on sustainability and social responsibility, the city draws objectives aimed at improving the population's quality of life, focusing on the reduction of its carbon footprint, in all sectors of urban planning.

Following the Memorandum of Understanding (MoU) on bilateral cooperation signed in 2013 between the Brazilian and Swedish Ministries of Environment, as well as subsequent agreements to promote sustainable urban development in Curitiba e.g. the project “Smart city concepts in Curitiba – innovation for sustainable mobility and energy efficiency”, led by the Royal Institute of Technology (KTH) in Sweden, positive synergy effects were identified for a cooperation between SMHI and the Municipality of Curitiba focusing air pollution.

The “Particles in Curitiba” (ParCur) project was planned in the end of 2015 and the cooperation agreement between the Curitiba municipality and SMHI was signed in March 2016. The first phase evaluated current particulate matter (PM) and black carbon (BC) sources and their impact on the Curitiba air quality. It started in December 2015 and ended with a seminar held in Curitiba June 2017, at which the preliminary results were presented.

Immediately after the June workshop, the regional environmental authority IAP announced that the state of Paraná has initiated a plan for implementing a more strict legislation concerning emissions to the atmosphere (see <https://www.metrojornal.com.br/foco/2017/06/20/parana-cria-plano-para-controlar-poluicao-ar.html>). The plan has as a goal to introduce new air quality limit values for Paraná, in a similar way that has been made in Sao Paulo. IAP has noticed that the national limit values presently in use are not compatible with the recommendations of the World Health Organization (WHO) and they do not cover fine particles such as PM_{2.5} which are considered harmful to human health. In order to support the new plan for a more strict legislation in Paraná, the reporting of ParCur results will include a comparison of how the present air quality compares to not only the present Brazilian legislation, but also to the European air quality directive and the WHO recommendations. During a follow-up ParCur workshop 5th-7th December 2017, these comparisons of how the Curitiba air quality compares to a more strict legislation were presented and they are also high-lighted here below.

This report summarizes the details and findings of the first phase. The second phase began on January, 2018, after the presentation of the results to the Brazilian counterparts. A separate document will detail the objectives for and activities of this second phase, which will have a duration of approximately one year. The idea is to assess different urban planning scenarios with respect to their effects on the future air quality in Curitiba.

The activities of the first phase include:

- Collect existing air quality and meteorological data for the last years.
- Design and perform a monitoring campaign for environments where people are exposed in high concentrations (street canyon environments) and over longer times (residential areas).
- Develop an emission inventory for nitrogen oxides (NO_x), PM and BC suitable as input to dispersion models with high spatiotemporal resolution.
- Implement dispersion models on the regional, urban and local scale.
- Perform an integrated analysis to adjust and validate the emission inventory
- Present a source apportionment with different sectors emissions and their contribution to present NO_x, PM and BC levels.
- Map NO_x, PM and BC levels and identify hot-spots.
- Compare the present air quality concentration levels with the current legislation, as well as with the European air quality directive and with the WHO recommendations.

Details of the results of each of these activities are found in the report that follows. For this executive summary, the results are given as conclusions and suggestions for future work.

Conclusions

The analysis of existing air quality data and the results of the ParCur wintertime monitoring/modeling campaign 2016 gives the following main conclusions:

- The air quality in Curitiba comply with existing Brazilian regulation concerning PM₁₀ and NO₂. A comparison with European air quality standards shows that daily PM₁₀ values at the IAP CIC station exceeds the EU limit values. The wintertime monthly averages of NO₂ in a street canyon and PM_{2.5} in one residential area obtained during the ParCur campaign indicate possible exceedances for the annual standards, however this should be more carefully analyzed through long-term measurements covering at least one year.
- There is a relatively large contribution to NO_x levels coming from sources southwest of the Curitiba municipality, mainly from the Araucária area, that is superimposed upon the high traffic impact along the ring road. Model simulations reveal typical wintertime urban background NO_x values of 40-70 µg/m³, of which at least half originates from sources outside the Curitiba municipality, most linked to the industrial sector.

- Urban background levels of BC are fairly homogeneously distributed over Curitiba with a wintertime mean concentration of about 2-2.5 $\mu\text{g}/\text{m}^3$, of which half comes from local traffic exhausts. There is no emission inventory of industrial contributions to BC, but it is likely that a considerable part of the remaining contribution comes from industrial sources outside the Curitiba municipality.

BC is not regulated, but local traffic contributes to high concentrations in traffic environments, typically doubling the urban background concentrations. Present BC levels in Curitiba are comparable to historic levels registered e.g. in Stockholm some 10-15 years back. In Sweden these levels have been strongly reduced during the last 10 years and a similar development should be possible in Brazil if vehicle technology is improved.

- While BC urban background concentrations are homogeneously distributed over Curitiba, there are strong gradients in $\text{PM}_{2.5}$ over at least some parts of the city. Urban background $\text{PM}_{2.5}$ levels are fairly low in the city center, in line with the WHO recommended levels, but measurements in a residential area in southern Curitiba indicate a strong impact of some unknown local sources. An analysis of the elemental and organic carbon fractions of the particles sampled in this residential area, indicate the possibility that wood or biomass combustion takes place there. Within this residential area, the $\text{PM}_{2.5}$ levels obtained during one month indicate an annual average exceeding the WHO recommendations.

The following two figures ES1 and ES2 give an overview of how the present air quality in Curitiba compares to different standards and recommendations, and they also summarize the new information on air quality levels collected inside a highly trafficked street canyon.

unit: $\mu\text{g}/\text{m}^3$	PM_{10} annual	PM_{10} daily	$\text{PM}_{2.5}$ annual	NO_2 annual
Brazilian legislation	50 ✓	150 ✓	-	100 ✓
EU air quality directive	40 ✓	50* !	25 ✓	40 ?
WHO guidelines	20 !	50 !	10 !	40 ?

*expressed as 90th percentile

Figure ES1 Overview of limit values and recommendations for PM_{10} , $\text{PM}_{2.5}$ and NO_2 in ambient air. From the results obtained in ParCur phase 1, three indicators have been attributed to each of the reference levels to demonstrate if current levels are compliant or not:

✓ = the observed and modelled concentrations in Curitiba are compliant

? = the observed and modelled concentrations in Curitiba are close to the limit value or the

recommendation, further assessment should be made to conclude if compliant or not

! = the observed and modelled contrations in Curitiba is not compliant



Figure ES2 Overview of how local traffic can increase air pollution levels inside a street canyon in Curitiba, adding to the urban background levels registered at roof level. Measurements made in the Marechal Deodoro street canyon. *Note:* The photo is from another street, used for illustrating how the buildings contribute to a canyon-like structure with reduced ventilation (also illustrated in the figure to the left).

Suggestions for future work

Based on the main conclusions of the ParCur first diagnostic phase, the following suggestions are given:

- As part of the plan for defining new air quality limit values in Paraná, install a couple of PM_{2.5} monitors to obtain a full year of data. Also NO₂ should preferably be followed for a full year in the locations where ParCur has indicated high levels (in highly trafficked street canyons and in the southwestern part of the city where industrial emissions are high).
- Assess the possibility of lowering the population exposure to harmful pollutants in traffic environments, e.g. by improved vehicle technology and more sustainable mobility systems. The second phase of the ParCur project offers a possibility to evaluate some future transport solutions and their impact on PM_{2.5}, BC and NO_x levels.

- Through inspections, interviews and/or questionnaires investigate the possible existence of combustion sources around Sitio Cercado, contributing to high PM_{2.5} and organic carbon levels. There are possible ways of reducing, in the short term, the impact of wood combustion through information of better practices, e.g. using dry wood and sufficiently provision of oxygen to the combustion process. If the combustion takes place in heating and/or cooking devices, a regulation and/or stimulation to switch to better technology can also be made. Residential waste burning in open air should preferably be regulated and controlled. The municipality is considering a campaign targeting citizens to elucidate on this issue of biomass combustion contributing to air pollution.
- Assess the possibility of lowering the pollution contributions of NO_x, PM₁₀ and BC from the industrial sources outside the Curitiba municipality. This can be made by identifying the largest emission sources and evaluate if better technologies can be used to lower the impact.

Note that these suggestions are given with the purpose to lower population exposure to long-term air pollutants that are affecting the health and to assure compliance of a future stricter legislation that is expected to be defined for the Paraná state. As stated in the conclusions, air pollutant concentration levels in Curitiba comply with the current Brazilian legislation. A second purpose of the suggestions is also to mitigate the emissions of black combustion particles (BC) that affect the regional climate and forms part of the so called Short-Lived Climate Pollutants (SLCPs).

2 Introduction

2.1 Project background

Atmospheric particles of inhalable size, often quantified as the mass of particles with an aerodynamic diameter less or equal to 10 (PM_{10}) or 2.5 ($PM_{2.5}$) micrometer, are linked to strong health effects on urban populations (WHO, 2012). Except for the health impact, the particles include light-absorbing soot – in what follows referred to as black carbon (BC) – which is an important short-lived climate pollutant (SLCP) that contributes to global warming (Bond et al., 2013).

The transport sector, in particular through diesel fueled heavy duty vehicles, constitutes an important source of particles and BC in ambient air. Another important source is biomass combustion, common in certain types of agriculture and in urbanized areas where restaurants and individual houses in residential areas burn wood and coal for cooking and – in some parts of Brazil – for heating. Apart from these sources, present in many Swedish and Brazilian cities, combustion processes like forest fires and those occurring in industrial processes with poor technology will also deteriorate the air quality due to high particle emissions. For all these combustion sources, and in particular for those that take place inside urbanized areas, there are strong synergy effects on health and climate by reducing PM and BC emissions.

The Swedish Ministry of Environment maintains and searches for bilateral cooperation with environmental authorities in other countries. In November 2013, a Memorandum of Understanding (MoU) to cooperate in the fields of environmental protection, climate change and sustainable development was signed between the Swedish and Brazilian Ministries of Environment. One of the listed areas of cooperation is air pollution monitoring and control, as well as pollution abatement and prevention of BC and tropospheric ozone.

In 2014 the Swedish Ministry of Environment offered funding for a bilateral cooperation between the Swedish Meteorological and Hydrological Institute (SMHI) and the regional environmental authority in Rio Grande do Sul State, Fundação Estadual de Proteção Ambiental Henrique Luiz Roessler (FEPAM). Together, SMHI and FEPAM formulated a pilot project to assess emissions and impact of $PM_{2.5}$ and BC in Sapiranga, a typical mid-sized city in the region. The Sapiranga project also involved the Prefeitura Municipal de Sapiranga and air quality experts from the Universidade Federal de Pelotas (UFPel), Universidade Tecnológica Federal do Paraná (UTFPR) and Centro Mario Molina Chile. The results of this pilot project have been presented in the report by Gidhagen et al. (2015). The Sapiranga cooperation project developed a method to assess the emissions and the impact of $PM_{2.5}$ and BC in urban outdoor environments, with the overall objective of identifying ways of lowering the emissions of the city and reducing the health effects on the exposed population. Within a relatively short period of time, the pilot project revealed important conclusions on the contribution of different sources to particle pollution in the city by using a combined approach of air pollutant emission inventories, local air quality measurements, and dispersion modelling.

The city of Curitiba has gained worldwide prominence for its efficient practices in urban planning and public transport. Engaged in projects on sustainability and social responsibility, the city draws objectives aimed at improving the population's quality of life, focusing on the reduction of its carbon footprint, in all sectors of urban planning. As recognition of this commitment, Curitiba was selected as one of the eight cities in Brazil to participate in the Urban Low Emissions Development Strategy (Urban-LEDS) project, with the goal of enhancing the transition to low emission urban development in emerging economy countries through the integration of low-carbon strategies into all sectors of urban planning and development.

Although urban densification along mass transport axes is a tested concept in Curitiba, it requires that air quality impacts from transport vehicle exhausts (implying population exposure and ultimately effects on human health) are taken into consideration in the planning process. A sustainable urban development also requires that other pollution sources affecting Curitiba's air quality should be assessed and supervised. Aspects requiring further investigation are found especially in fields pertaining to the source-apportionment of emissions, the identification of pollution hot-spots (where critical air pollution levels can be attained), and the assessment of the effectiveness of strategies and plans for the mobility sector.

Following the MoU signed between Brazilian and Swedish Institutions to promote sustainable urban development in Curitiba and the project "Smart city concepts in Curitiba – innovation for sustainable mobility and energy efficiency" led by the Royal Institute of Technology (KTH) in Sweden, positive synergy effects were identified for a cooperation between SMHI and the Municipality of Curitiba. This cooperation aims at assessing the sectorial contribution to air pollution (including the road transport sector) and quantifying the co-benefits on air quality and health of different actions driven by other objectives, such as the improvement of urban mobility, promotion of energy efficiency and the reduction of greenhouse emissions.

In order to evaluate the interest of an air quality project study, complementing the "Smart city concept" project, a prospect visit to Curitiba was held between the 9th and the 12th of June 2015. An extensive number of meetings with top-level representatives from local government agencies and R&D poles was organized by Curitiba's International Affairs Office (ARIN) to identify specificities and needs of Curitiba on the air pollution field; assess strategies, plans and available data; capture potential partners; formulate common objectives and an activity plan; and identify roles and responsibilities. In the presence of a large number of potential partners attending a meeting organized by the municipality, the general objectives and the first outline of a workplan for a bilateral cooperation project named "ParCur" (*Particles in Curitiba*) was presented. The ParCur workplan was separated into two phases.

The first phase, comprising the evaluation of current PM_{2.5} and BC sources and their impact on Curitiba's air quality, started in December 2015 and ended with a seminar held in Curitiba in June 2017, where preliminary results were presented. Immediately after the June workshop, the regional environmental authority IAP announced that the

state of Paraná has initiated a plan for implementing a more strict legislation concerning emissions to the atmosphere (see <https://www.metrojornal.com.br/foco/2017/06/20/parana-cria-plano-para-controlar-poluicao-ar.html>). The plan has as a goal to introduce new air quality limit values for Paraná, in a similar way that has been made in Sao Paulo. IAP has noticed that the national limit values presently in use are not compatible with the recommendations of the World Health Organization (WHO) and they do not cover fine particles such as PM_{2.5} which are considered harmful to human health. In order to support the new plan for a more strict legislation in Paraná, the reporting of ParCur results will include a comparison of how the present air quality compares to not only the present Brazilian legislation, but also to the European air quality directive and the WHO recommendations. During a follow-up ParCur workshop 5th-7th December 2017, these comparisons of how the Curitiba air quality compares to a more strict legislation were presented and they are also high-lighted in the Executive summary of this report.

This report thus summarizes the findings of the first phase. The second phase started in the second half of 2017 and will have a duration of approximately one year.

The main counterpart of this bilateral cooperation project, being the principal stakeholder and target for the new knowledge coming out of ParCur, is the Municipality of Curitiba. The technical coordination of the project is shared between SMHI and UFPR. Main actors during the first phase have been the institutions contributing to this report: UTFPR, UFPEL, IPPUC, URBS, SMMA, IAP and DETRAN. However, ParCur is open to all institutions with interest in the air quality of the city. Other local and regional institutions that have participated in a number of meetings and seminars are SMS, UP, PUCPR, SEPLAD, SETRAN, SIMEPAR and LACTEC. From the Swedish side KTH and SEPA have also taken part in ParCur seminars and discussions. In Appendix 1 there is an overview of institutions and contact persons that took part in the planning and the realization of the first ParCur phase (*note that some contact details may have changed*).

General objectives

The bilateral cooperation should benefit the knowledge and skills of both the Brazilian and Swedish partners concerning the emissions and impact of PM and BC. There are two general objectives, linked to the two phases of the project:

- Describing the present emissions and concentration levels of respirable PM and BC in Curitiba, their spatial and temporal variation, and identifying the main sources and their contribution to total levels.
- Projecting the future concentration levels of PM and BC in Curitiba, for different mobility scenarios, identifying ways of achieving a sustainable development of urban infrastructure that protects the health and quality of life of the city inhabitants, as well as helps to reduce the emissions of particles that contribute to climate warming.

Specific objectives

Phase 1: Analysis of the current air quality in Curitiba and metropolitan region

- Collect existing air quality and meteorological data for the last years.
- Design and perform a monitoring campaign for environments where people are exposed in high concentrations (street canyon environments) and over longer times (residential areas).
- Develop an emission inventory for NO_x, PM and BC suitable as input to dispersion models with high spatiotemporal resolution.
- Implement dispersion models on the regional, urban and local scale.
- Perform an integrated analysis to adjust and validate the emission inventory
- Present a source apportionment with different sectors contribution to present NO_x, PM and BC levels
- Map NO_x, PM and BC levels and identify hot-spots.
- Compare the present air quality concentration levels with the current legislation, as well as with the European air quality directive and with the WHO recommendations.

Phase 2: Scenario modelling

- Assess scenarios for new technologies introduction in mass transport corridors.
- Assess scenarios following different urban planning options or other alternatives proposed by end-users and stakeholders.

2.2 Curitiba city

Curitiba is located in the morfostructural unity of Parana First Plateau, bordered on the west by the “Devonian Scarp” and on the east by the “Serra do Mar”, a mountain range situated along the Brazilian south and southeast coasts (Maack, 2012). The city has an estimated population of 1,864,416 inhabitants (IBGE, 2014) with an average density of 4,024 inhabitants/km². From the urbanistic standpoint it is important to highlight the Serete Plan, developed in 1964 and applied in the 1970's, as the backbone of the development strategy that shaped the city's current structure and morphology (Santos, 2014). The plan organized the municipality using the triad: Public Transportation, Land Use and Road System, which led to the creation of the “structural axes”. The axes consist of transport corridors that integrate land use and transport strategies. Each axis is formed by three parallel roads in which the central one is dedicated to the Bus Rapid Transit (BRT) system, and the adjacent ones, called “fast ways”, contain four or more traffic lanes in only one direction. The axes originate in Curitiba's city center with their

BRT lines in five different directions: South (Sete de Setembro and República Argentina Avenues), West (Padre Anchieta Street), East (Presidente Afonso Camargo Avenue), North (Paraná Avenue) and Southeast (Marechal Floriano Peixoto Avenue). Recently, the reconstruction of highway BR-116 has been designed to be transformed into a new structural axis (the Green Line). Figure 2.2.1 shows in red the axes mentioned above.

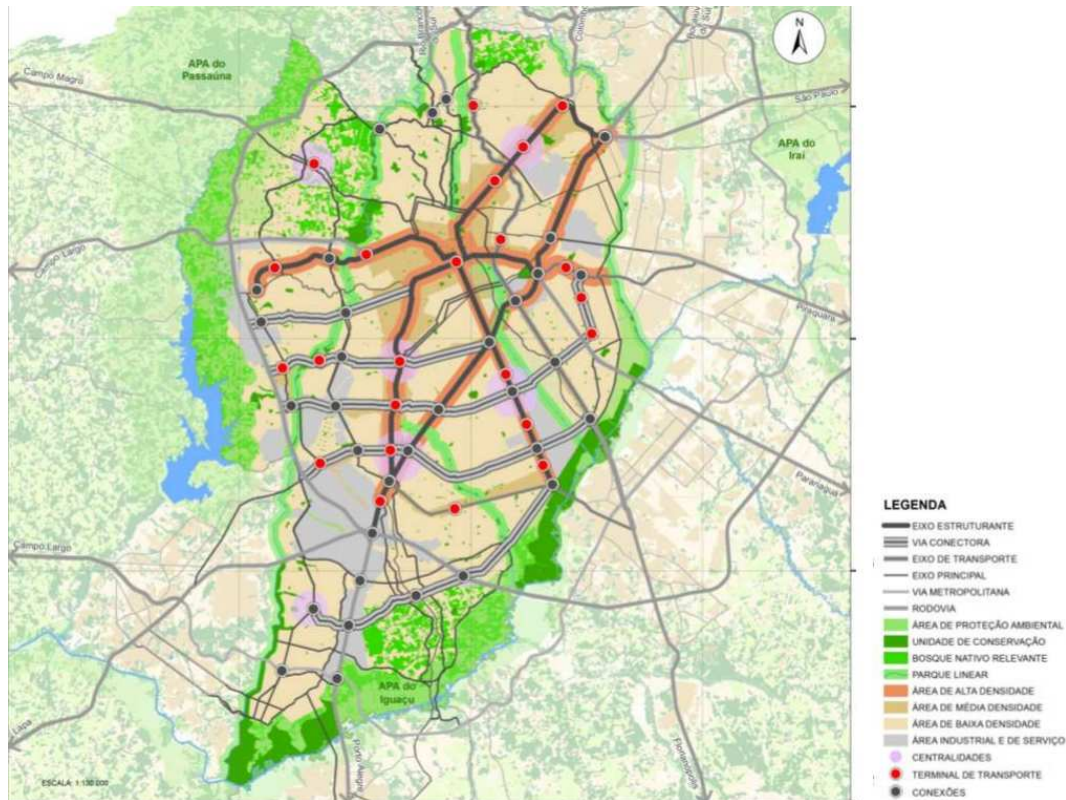


Figure 2.2.1 Curitiba's structural axes. Source: IPPUC (2014).

The urban growth of Curitiba over the last twenty years is shown in Figure 2.2.2. The grey area indicates the city limits obtained from a satellite image in 1986; the red area and dots indicate the city expansion as of 2009 (Galvão, 2011). The city expanded mostly towards the southwest direction, far beyond the city center, reaching areas with limited infrastructure, such as lack of basic sanitation system or close to rivers and spring water sources. That is a typical characteristic of developing countries in which the urban growth takes place faster in areas where the land prices are lower but the location is not the most appropriate.

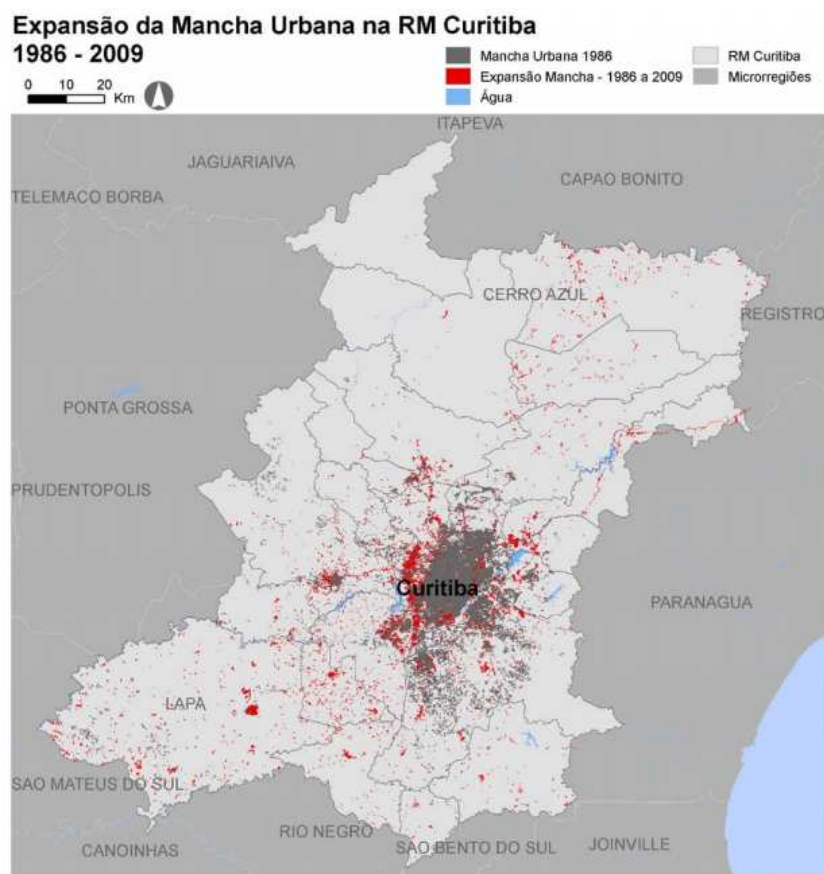


Figure 2.2.2 Urban area expansion of Curitiba's metropolitan region in 1986-2009.
Source: Galvão (2011).

Danni-Oliveira and Mendonça (2007) classified the climate of Curitiba as humid subtropical with cold winters. The climate conditions are dominated by tropical (continental and Atlantic) and polar air masses. In the summer months the Equatorial air mass also affects the weather in the region. The rainfall is well distributed through the year with an average amount of 123.6 mm/month or 1483 mm/year. The driest month is July and largest rainfall occurs in January (Figure 2.2.3). The high altitude of Curitiba (average of 970 m) contributes to the low temperatures, which occur in August (average of 10 °C).

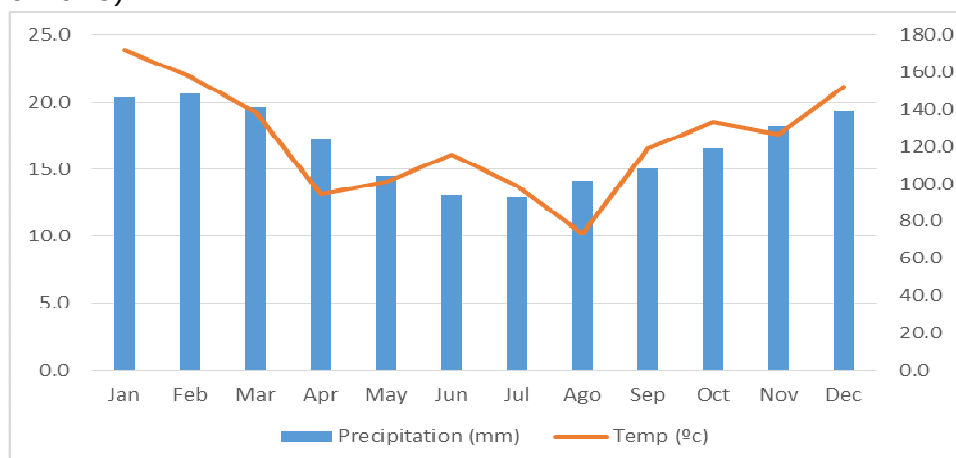
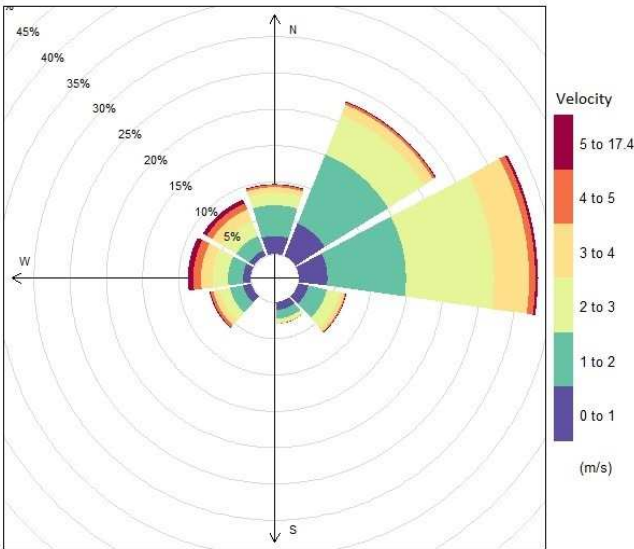


Figure 2.2.3 Climate normals for Curitiba (1961-1990)

The prevailing winds are from the east and northeast with an average speed of 1 m/s during the whole year (Fig. 2.2.4). When disaggregated by season, no substantial change is observed in the wind direction or intensity when compared to the annual average (Fig. 2.2.5), except that north-easterly winds become slightly more dominant in June, July and August.



Figure

2.2.4 – Wind rose for Curitiba (2004 - 2015)

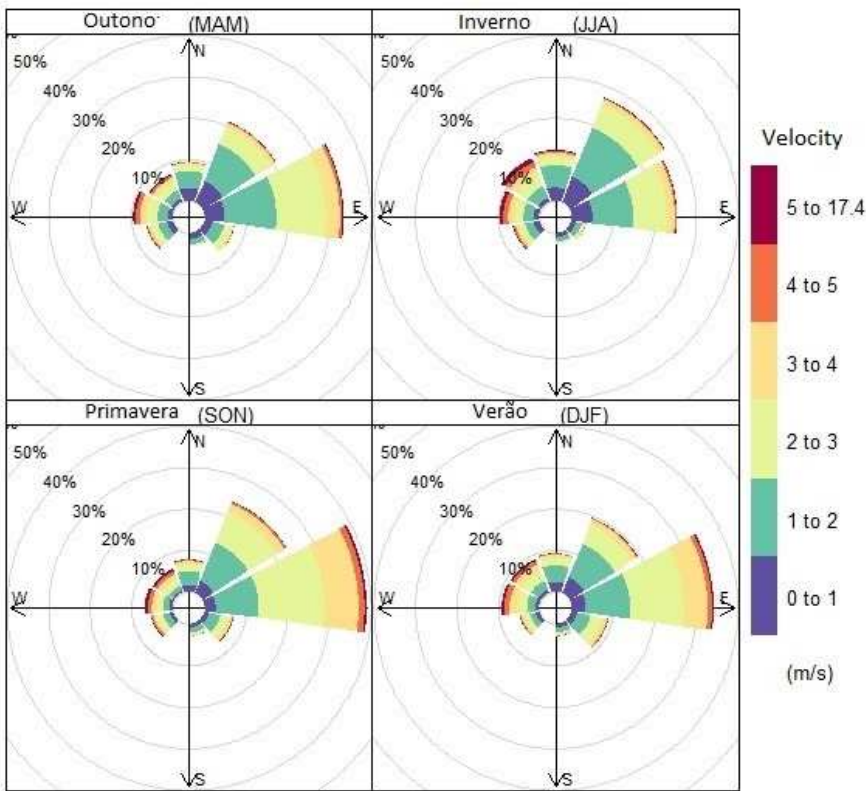


Figure 2.2.5 – Wind roses for Curitiba divided by season with autumn MAM (upper left), winter JJA (upper right), spring SON (lower left) and summer DJF (lower right) (2004 - 2015)

3 Methods

3.1 Experimental design

This section describes the methods used to monitor the air pollution levels, to build-up an emission inventory, verify emission factors by comparing monitored and model simulated pollution levels and implement the dispersion models to map the pollution levels over the city. The basic approach used to estimate the PM_{2.5} and BC emissions together with their impact on air quality is illustrated in Fig. 3.1.1:

1. Use local activity data and emission factors from the literature to create an emission inventory for the sources that are expected to contribute most to PM_{2.5} and BC levels (traffic, different types of combustion, industrial processes, etc)
2. Compile existing air quality and meteorological data, complemented by performing a monitoring campaign to collect PM_{2.5} and BC concentrations in areas where different sources are expected to dominate.
3. Perform regional dispersion modeling to look for long range transport signals that can contribute to the total concentrations as registered by Curitiba monitors. Use local dispersion models with input of local meteorology and atmospheric emissions from the inventory (1) to create maps showing the simulated effect of emissions on air pollution levels. Compare model results with monitored data from the operational monitoring network and from the ParCur monitoring campaign and conclude on the magnitude of the emissions. Major differences should imply modifications of emissions until an acceptable resemblance between simulated and monitored levels are obtained. In this way we can assess and control the quality of the emission inventory. It is recommended to start the emission validation (Fig. 3.1) in a well-controlled environment where a specific source is dominating. For ParCur this starting point is the street canyon, to assess the impact of the traffic flowing through a particular road link.



Figure 3.1.1 Concept for validating emissions (see point 1-3 above)

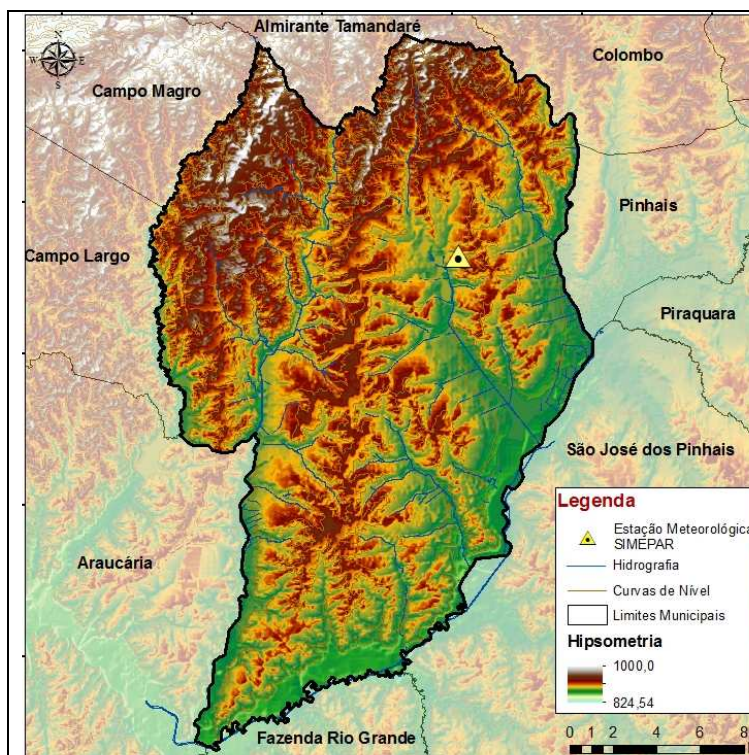
After having a credible emission inventory it is possible to perform scenario modeling, which means to perform changes in the emissions inventory that reflect certain actions, e.g. improved technology of dominating sources or replacement of polluting activities that contribute to PM_{2.5} and BC reductions. The model will give quantitative estimates of the effect of different actions. The present report describes the work conducted in 2016-2017 and does not include the scenario modeling.

3.2 Meteorological information

The meteorological information used for the ParCur analysis and as input to the local dispersion models was taken from the SIMEPAR station (location indicated in Figures 3.2.1 and 3.3.1).

Figure 3.1

Topographic map of the Curitiba municipality, with location of SIMEPAR meteorological station.



3.3 Air quality monitoring

Overview of existing network and design of a complementary monitoring campaign

Data from 2013-2015 have been collected from the IAP network and the SIMEPAR meteorological station, and also for the monitoring campaign conducted in the period July 25 – August 25, 2016. Fig. 3.3.1 shows the stations for which the data have been analyzed (stations' UTM coordinates are listed in Appendix 2).

Fixed monitoring stations



IAP network:

- **PAR:** Praça Ouvidor Pardiniho: PM10, NO2/NOx
- **BOQ:** Boqueirão: PM10
- **CIC:** Cidade Industrial: PM10, NO2/NOx
- **STC:** Santa Cândida: NO2/NOx



SIMEPAR meteorological station

Campaign July-Aug 2016:



- M. Deodoro (street): PM2.5, BC
- M. Deodoro (roof level): PM2.5, BC
- Sítio Cercado (residential): PM2.5, BC



- M. Deodoro (street): NO2/NOx
- M. Deodoro (roof): NO2/NOx
- Vicente Machado (street): NO2/NOx
- Mercês (urban backgr.): NO2/NOx
- Xaxim (urban backgr.): NO2/NOx
- Vila Petrópolis (urban backgr.): NO2/NOx
- Alto da Glória (urban backgr.): NO2/NOx
- Alto da Rua XV (urban backgr.): NO2/NOx
- Bairro Alto (urban backgr.): NO2/NOx
- Batel (urban backgr.): NO2/NOx
- Cajuru (urban backgr.): NO2/NOx

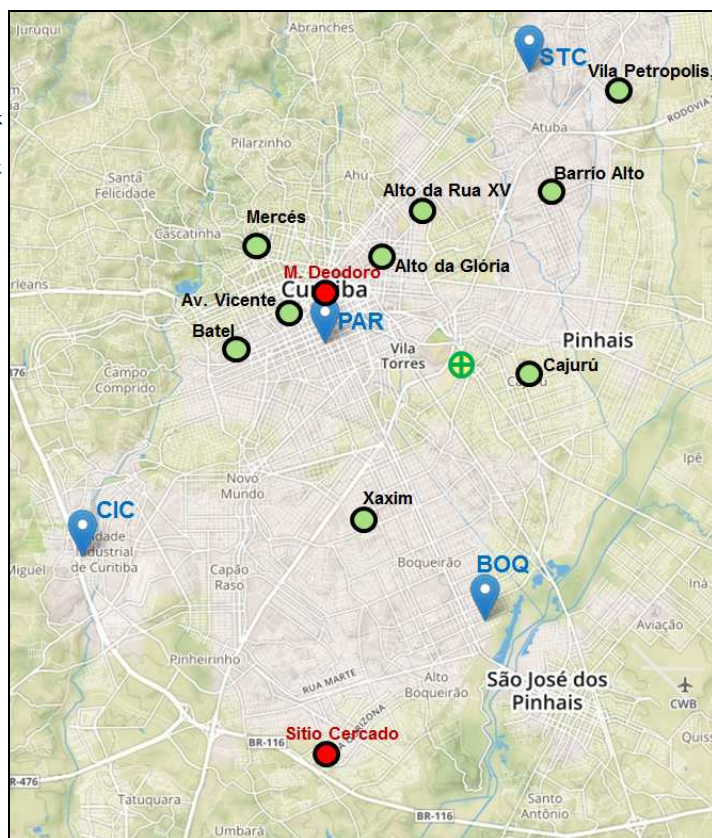
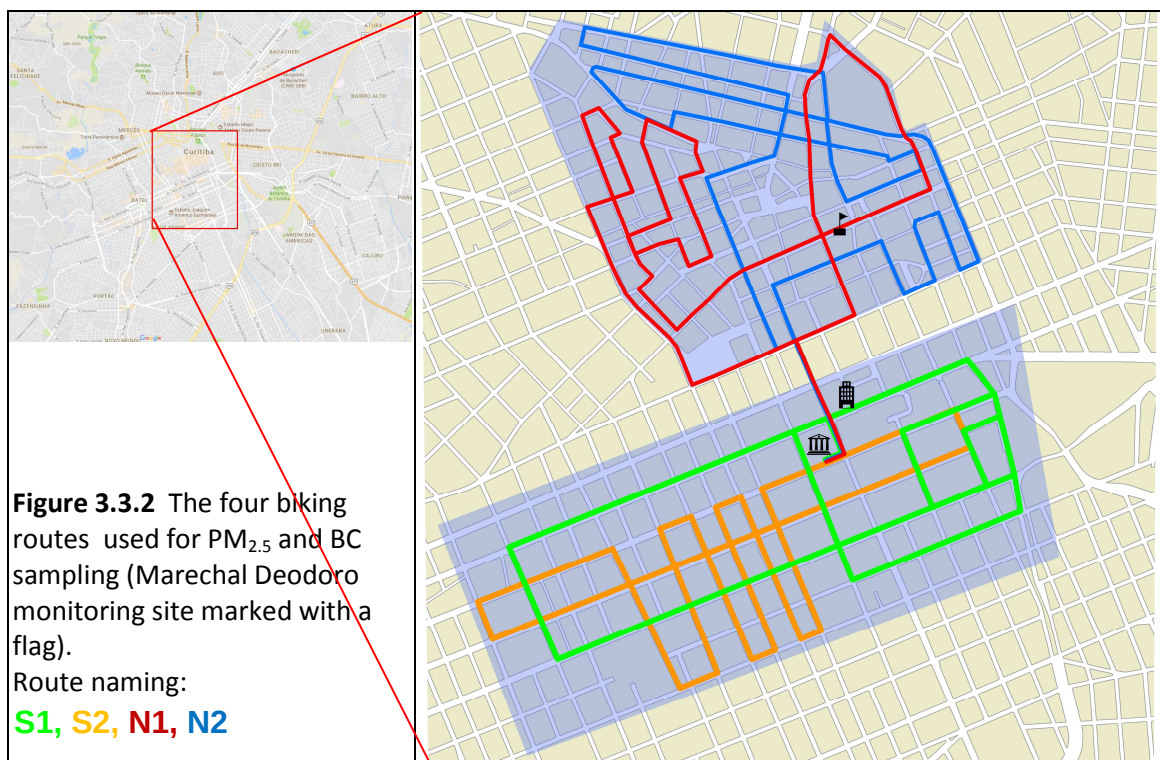


Figure 3.3.1

Overview of fixed monitoring stations used in ParCur.

The monitoring campaign, carried out in the winter of 2016, included three fixed stations to measure PM_{2.5} and BC, plus 11 stations for passive sampling of NO₂/NO_x.

The mobile monitoring of PM_{2.5} and BC, using bikes, was performed along four different routes in the city center, with different road configurations and traffic intensities (Fig. 3.3.2). Two routes were defined within the low-speed zone, which has a speed limit of 40 km h⁻¹, and two other routes were settled within an area with regular speed limit (max 60 km h⁻¹). Each study region covered an area of approximately 2.50 km². Route N1 was designed to include stops at the fixed monitoring site located on Marechal Deodoro Street, a one-way, four-lane road aligned with the east-west direction with high traffic volume (24075 veh day⁻¹) and intense commercial activity. This road is formed by tall buildings flanking both sides of the street in a typical canyon configuration.



PM10 and NO_x monitors from the IAP network

IAP-PAR: Monitors of PM₁₀ and NO_x. Station located in the SW corner of a square. Traffic not very intense. Some trees along the nearest road and low buildings outside the park. Intake situated above a container-like building, approximately at 3 m high. The station is a mixture of a traffic and urban background station.

IAP-BOQ: Monitor of PM₁₀. Station located in a residential area, with the intake above a container at approximately 3 m of height. Low buildings around and low traffic on the roads around the block, 300-400 m to more trafficked roads towards the east.

IAP-CIC: Monitors of PM₁₀ and NO_x. Station located in Cidade Industrial de Curitiba, about 200 m east of the ringroad which is heavily trafficked and has a large proportion of trucks which are not allowed to pass through the city. Intake at approximately 3 m high, located above a container with no high buildings around. The station is an urban background station, but in an area with a lot of heavy traffic and possibly more local industrial activities that can generate PM emissions.

IAP-STC: Monitor of NO_x. Station located in a residential area up on a small hill, with a lot of trees and a park-like environment. A residential station with low traffic volumes around.

PM_{2.5} monitoring

PM_{2.5} monitoring was accomplished with three types of instruments:

- Harvard Impactor (deployed at the canyon site: street and rooftop levels)
- Ecotech sampler (installed at Sítio Cercado)
- DustTrak (one unit deployed at Sítio Cercado and two units used for mobile measurements)

Harvard Impactor

PM_{2.5} samples for mass concentration analysis were collected on 37 mm teflon filters on a daily basis, using Harvard Impactors operated with an air flow of 4 liters per minute (LPM). In this instrument, the ambient air is pumped through a nozzle, where the air flow and particles are accelerated. The air flow is directed towards an impaction plate and diverted along a defined path. The particles are diverted along the air flow, with the deflection angle depending on the mass of the particle and its velocity. Heavier particles deviate less and hit the plate, while the lighter particles flow until being collected on the filter. In this study, we used a nozzle designed to measure PM_{2.5} when operated at a flow of 4 LPM (Marple et al., 1987; see Fig. 3.3.3).

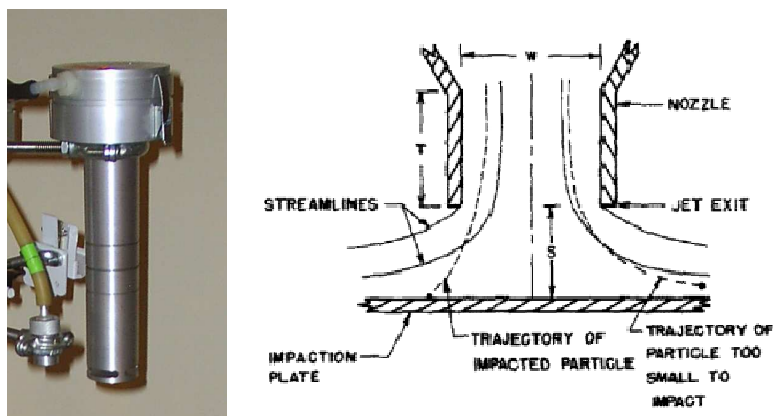


Figure 3.3.3 Harvard Impactor device for PM_{2.5} (left). Operating diagram of an impactor (right, Marple et al., 1976).

Ecotech sampler

Daily integrated samples for gravimetric, elemental carbon (EC) and organic carbon (OC) analysis were collected using a low-flow air sampler model 1100 (Ecotech, Australia) deployed at Sítio Cercado. This sampler was equipped with an impactor inlet of 2.5 µm cut-off size installed at 2 m above ground level. Aerosol particles were sampled on 47 mm Tissuquartz 2500QAT-UP quartz fibre filters (Pall Corporation, USA) at a flow rate of 3 LPM.

For mass determination, gravimetric analysis was performed on all filters collected at the street canyon and at Sítio Cercado sites following the NIOSH Method 0500, at the UFPR laboratory. Quartz fiber filters were weighted before and after sampling using a ultramicro balance (Sartorius, MAS.7S-000-DF). Before of each weighting, the filters were placed in clean glass Petri dishes and previously conditioned at a temperature of $20 \pm 1^\circ\text{C}$ and at relative humidity of $50 \pm 5\%$ for at least 24h. EC and OC were analyzed from the Ecotech sampler filters at Sítio Cercado. Samples for EC/OC determination were collected on pre-fired (800°C , 3 h) quartz fibre filters and were analyzed by a thermal-optical transmittance (TOT) method using a Thermal/Optical Carbon Aerosol Analyzer (Sunset Laboratory Inc., USA), following a NIOSH temperature protocol (Birch, 2003) at the Department of Environmental Science and Analytical Chemistry, Stockholm University. The blank correction, which is the simplest correction method for positive artifact, was applied.

DustTrak aerosol monitor

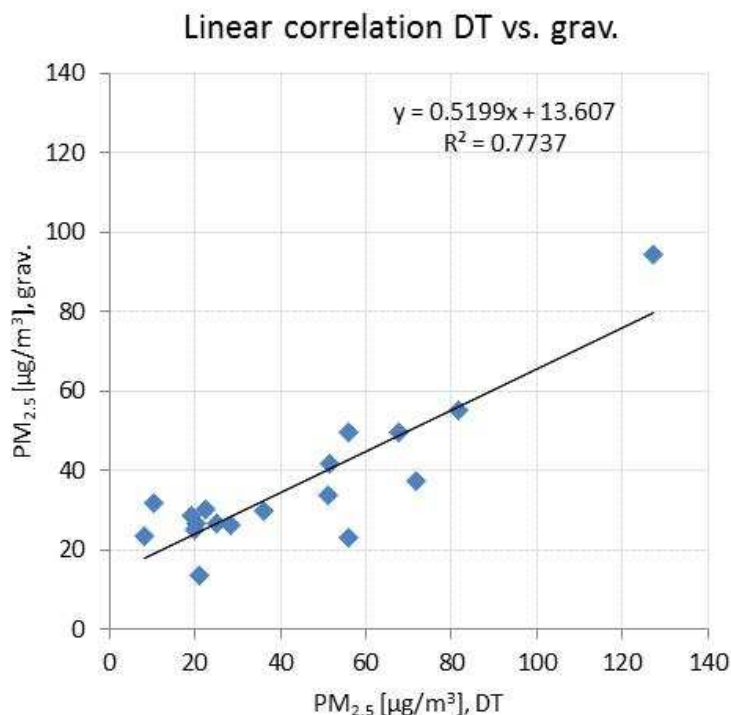
We used the DustTrak equipment (model 8520, TSI) to monitor $\text{PM}_{2.5}$ mass concentrations at a sampling frequency of one minute at the fixed monitoring site (Sítio Cercado) and 10 seconds for the mobile measurements (city center). The instruments were operated at a flow rate of 1.7 LPM with an impactor to remove particles larger than $2.5\ \mu\text{m}$ (shown in Fig. 3.3.4). The particles in the sample flow penetrate a chamber illuminated by a 780-nm laser, where a photodetector detects the radiation scattered by the particles. This method determines the particle volume by assuming the diameter of a spherical particle based on the scattered light's intensity, and subsequently derives the mass using the density of the respirable fraction of Arizona Test Dust aerosol ($\rho = \text{of } 2.6\ \text{g cm}^{-3}$). The mass concentrations reported by the DustTrak are usually larger than the real mass concentrations of the urban aerosol, because urban aerosols usually have a lower density. Thus concurrent gravimetric measurements at Sítio Cercado were used to yield the site-specific correction factor (see Figure 3.3.5 for more details). The two DustTrak units that were used for mobile measurements in the city center were also corrected assuming the same correction factor determined for Sítio Cercado.



Figure 3.3.4 DustTrak device used for $\text{PM}_{2.5}$ continuous measurement.

Figure 3.3.5

Calibration of optical instrument DustTrak used at station Sítio Cercado, against gravimetric data collected in parallel. The linear regression equation and coefficient of determination (R^2) are also shown.



BC monitoring

Measurements of BC concentration were carried out with two benchtop aethalometer models AE42 and AE33 (Magee Scientific, USA) installed at the canyon site at street level (inlet at 5 m high) and rooftop site (inlet at 70 m high), respectively, and one microaethalometer model AE51 (AethLabs, USA) was deployed at Sítio Cercado (inlet height at 2 m from the ground) and two were used for the mobile monitoring. The working principle of these instruments is based on the radiation-absorbing properties of carbonaceous aerosols, measuring the attenuation of electromagnetic radiation transmitted through particles that are continuously collected on a filter. The method assumes that the attenuation is linearly proportional to the BC mass loading on the filter and that there is no other absorbing material on the sample than BC particles. The BC concentration is related to the rate of change of attenuation via the wavelength-dependent cross sectional absorption coefficients σ_λ . A thorough description of its principle of operation can be found in e.g. Hansen *et al.* (1984).

The AE42 and AE33 instruments measure the attenuation at 7-wavelength radiation source wavelength (370, 470, 525, 590, 660, 880, and 950 nm) whereas the AE51 operates with an 880-nm radiation source.

The model AE51 was operated at a sampling frequency of 1 minute and a flow rate of 0.05 LPM at Sítio Cercado, whereas for the mobile measurements the sampling occurred every 10 seconds with a flow rate of 0.15 LPM. A site-specific σ_λ ($18.39 \text{ m}^2\text{g}^{-1}$) was calculated for the measurements conducted at Sítio Cercado by linearly correlating the EC concentrations with the concurrent mean BC concentrations determined with

the AE51 (see Fig. 3.3.6). Thus, all BC concentrations measured at Sítio Cercado with the AE51 were divided by 1.4712. The aethalometer measurements conducted in the city center (fixed site and mobile) used the σ_λ values setup by the corresponding manufacturers.

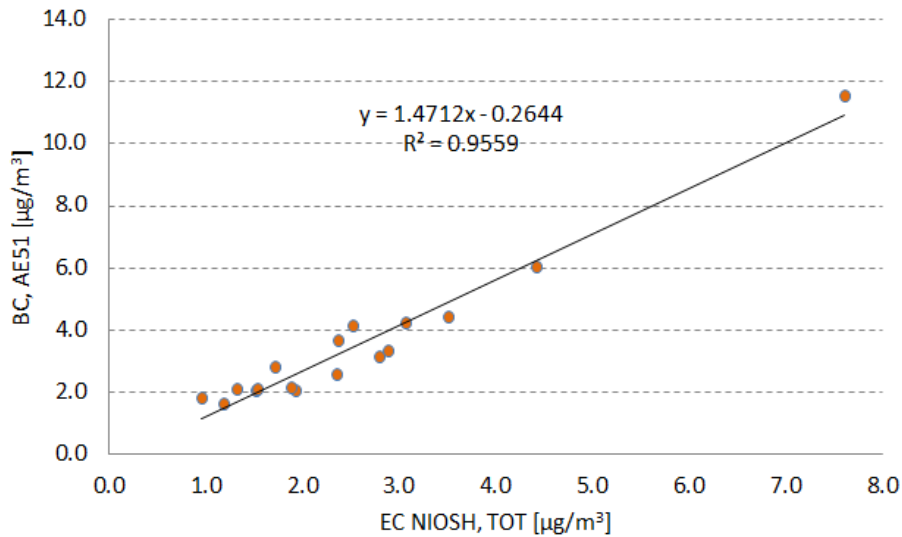


Figure 3.3.6 Scatterplot comparison of 24-h values of BC (AE51) and EC (TOT) mass concentrations conducted at Sítio Cercado. The solid line represents the least squares line regression; the linear regression equation and coefficient of determination (R^2) are also shown.

Bike mobile monitoring procedures

The mobile data collection consisted of 10 sampling sessions on weekdays and weekends between August 1 and 14, 2016 along four routes distributed within two areas in the city center. We use the term run to denote a sampling session covering an entire route. The runs always started simultaneously and at approximately the same time each day (8:00 am and 5:00 pm) to avoid hourly variability in traffic patterns. The runs lasted between 70 and 90 minutes depending on the route (Fig. 3.3.2).

The bicycles were retrofitted with an L-shaped carbon steel platform bolted to the stem of the handlebars, on which a heavy-duty tool bag was placed. A microaethalometer AE51 for BC measurements, a DustTrak 8520 for $PM_{2.5}$ measurements and a high accuracy GPS receiver and logger (DG-100, GlobalSat, Taiwan) were placed inside the heavy-duty bag and cushioned with foam to reduce vibration (Fig. 3.3.6).

Instrument preparation consisted of zero calibration checks, cleaning of the DustTrak impactor and chamber, changing of the AE51 filter strip, battery and memory checks, and clock synchronisation using a laptop connected to the internet to ensure clock accuracy. Flow measurements were performed with a factory calibrated flow meter (model 4100, TSI, USA). Instrument intercomparison occurred before and after each measurement session in which we left the bicycles standing side by side for approximately 20 minutes.

The temporal resolution was 10 seconds and the cycling speed was between 9.0 and 11.0 km h⁻¹.



Figure 3.3.6 Photos showing the mobile monitoring using bikes.

Passive sampler of NO₂/NO_x and analysis

The samplings of NO₂ and NO_x were performed using Ogawa samplers (2 cm in diameter and 3 cm in length, Ogawa & Company, Pompano Beach, FL, USA). The sampler has two chambers equipped with filters impregnated with absorbent solution (one filter is coated with triethanolamine (TEA) for sampling NO₂ and the other with TEA and 2-phenyl-4,4,5,5-tetramethylimidazoline-1-oxyl-3-oxide, for sampling NO_x, added to oxidise NO to NO₂). The filters are placed between two stainless steel screens secured by a Teflon diffuser end cap with 2 mm diameter holes (Hagenbjörk-Gustafsson et al., 2010). Once assembled, the sampler is placed into the plastic bag and into the plastic flask until sampling. After exposure, the above procedure is again followed until laboratory analysis. During the samplings, the entire sampler body was put into the support (4 x 3 cm), and a shelter protected the sampler from rain and sun (Figure 3.3.7).

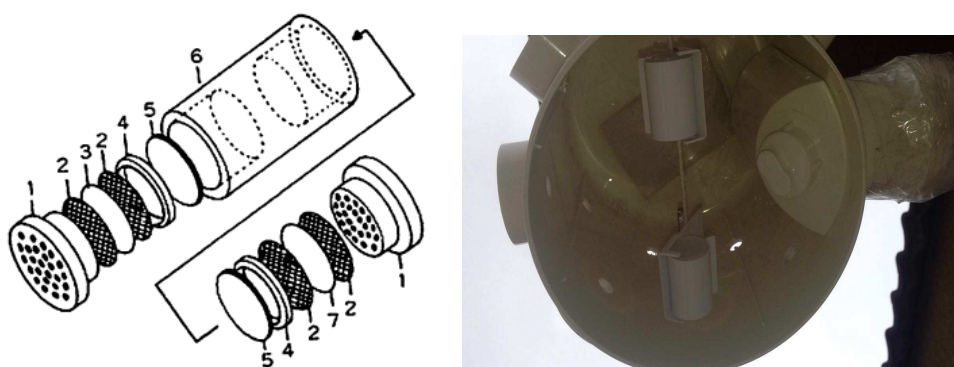


Figure 3.3.7 Schematic diagram of an Ogawa sampler: (1) diffuser end cap; (2) stainless steel screen; (3) coated NO₂ collection filter (14.5 mm in diameter); (4) Teflon ring; (5) Teflon disk; (6) body and (7) coated NO_x collection filter (14.5 mm in diameter) (left, Hagenbjörk-Gustafsson et al., 2010). Ogawa sampler in the support and protective shelter (right).

After sampling, the filters were analyzed at the UTFPR laboratory following the Ogawa Protocol (www.ogawausa.com/protocols.html, 2006). Analytical grade chemicals were used throughout this work. Ultra-pure water (Direct-Q, 5UV, Millipore) was used to prepare all solutions, and all materials were properly decontaminated with ultra-pure water. For analysis, each filter was placed into 25 mL glass vial containing 8 mL water, and shaken (Tecnal, TE-1400) for 30 min at 120 rpm, and then it was added 2 mL of the colorimetric solution (sulfanilamide 0.46 mol L⁻¹ solution mixed with solution of N-(1-naphthyl) ethylenediamine dihydrochloride 0.22 mol L⁻¹ in 10: 1 ratio, respectively). The reaction was held under 6°C for 30 min. After this, it was allowed to equilibrate at room temperature, then its absorbance was measured with a spectrophotometer at a wavelength of 545 nm (Varian, Cary 50). For NO and NO₂ determination, it was prepared an analytical curve in triplicate with sodium nitrite standard solutions ranging from 2.0 to 10.0 µg_{nitrite} mL⁻¹. For each sampling site, at least one unexposed filter was treated with the same procedure to obtain blank values. The difference signal between sample and blank was considered as the analytical signal.

Comparison with reference monitor and sampling sites

Ogawa samplers were compared to the chemiluminescence monitor used by Instituto Ambiental do Paraná (IAP) at the automatic air monitoring station of Ouvidor Pardiniho (PAR). The hourly NO₂ concentration determined in this station is then averaged from the beginning to the end of the sampling time. It was collected six replicates of the samples in one and two week and for comparison was carried out the sampling in the ground level of the station and near the chemiluminescence monitor (height at 3 m from the ground level) starting at June 27th and June 30th, 2016, respectively. After comparison, NO₂ and NO_x were sampled at ten different places (Fig. 3.3.1) in Curitiba (Centro, Alto da Glória, Alto da Rua XV, Bairro Alto, Batel, Cajuru, Mercês, and Xaxim) and one in Colombo (Vila Petrópolis), to assess the spatial distribution of nitrogen oxides over the city. The sampling time was two weeks and all samples were collected in duplicate at each point. The first passive monitoring campaign was from July 29th to August 12th, 2016, and the second one from August 15th to 29th, 2016.

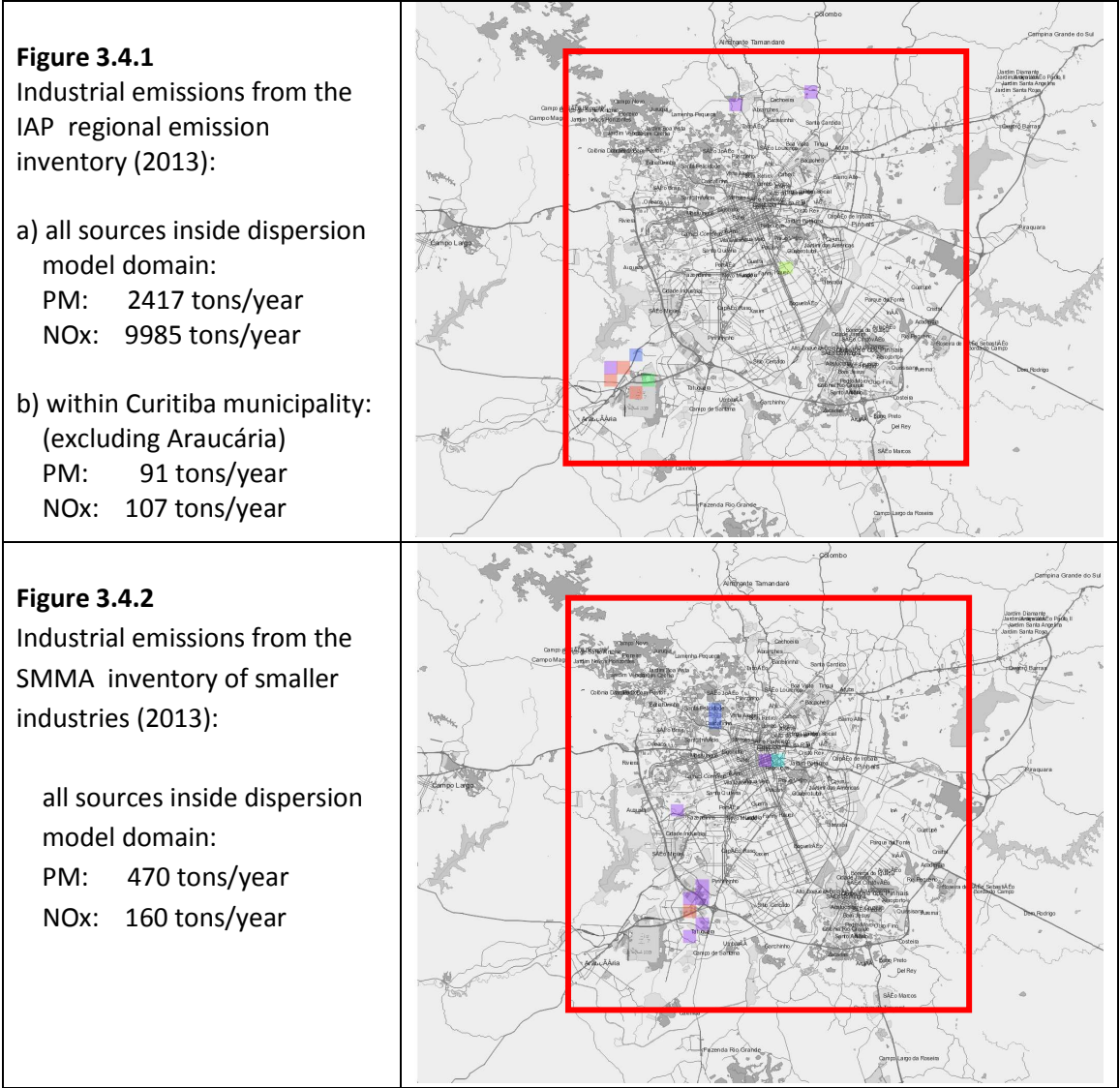
3.4 Emission inventory

Industrial point source emissions from existing IAP and SMMA inventories

Industrial emissions for larger industrial sources were taken from the regional inventory (IAP, 2013). Complementarily, emissions from smaller industries were provided by SMMA (personal communication). Fig. 3.4.1-2 shows the locations of major PM sources as given by the two inventories.

For the IAP inventory the dominating emissions are found outside the Curitiba municipality, within the Araucária industrial area. The impact simulations for all IAP sources outside the Curitiba municipality was made with the regional dispersion model. The impact of IAP sources within Curitiba municipality and the smaller sources

reported by SMMA was simulated by the local Gaussian model within the domain indicated by the red rectangle of Fig. 3.4.1-2.



Public transport emissions

Since the impact modeling of public transport, and the possibilities to reduce it by more sustainable technologies, is one of the main targets of ParCur, we have put a large effort in describing the emissions from individual bus lines. IPPUC has provided the shape files of the different bus lines, as well as a file containing the daily operations – in travel kilometers – of each line. Bus time tables for all bus lines have been downloaded from the internet and converted to normalized tables indicating the number of buses operating on a particular hour of the day and on a particular bus line. The file provided by IPPUC also indicates the company operating the bus line (Table 3.4.1).

URBS has provided a description of the technology used by different operators. In total there is a dominance of Euro III technology, with a smaller number of Euro II and a few Euro V Hybrids (Fig. 3.4.3).

Emission factors for NO_x, PM2.5, BC and fuel consumption were taken from the European model HBEFA (Table 3.4.2). Since fuel consumption was provided by URBS, we tried to find the signed speed and traffic situation corresponding to a similar HBEFA fuel consumption. The fuel consumption was also used to extrapolate emission factors for the bi-articulated buses, which are longer and heavier in Curitiba as compared to Europe.

The influence of bio-diesel on emissions was taken from a diagram published by the U.S. Department of Energy

(http://www.afdc.energy.gov/vehicles/diesels_emissions.html), indicating that particle emissions reduce by 50% and NO_x emission increase by 10%. The emission factors given in Table 3.4.2 consider the reduction on PM emissions, but neglect the rather small effect on NO_x emissions.

The database with individual bus lines has been used for simulating the impact on air quality over the entire city. For the more detailed model simulations in street canyons, the bus traffic has been transferred to an aggregated road link system, covering four routes in the city center from which air quality data from mobile measurements are available (see biking routes in Fig. 3.3.2). The road links along the biking routes were tailored for the street canyon model, typically covering one block and with well-defined house heights between 0 and 70 m on the two sides. The house heights were taken from laser data provided by IPPUC.

Table 3.4.1 Example of information provided for each bus line, here exemplified by line 550, one of the express lines operated by the largest bi-articulated buses. Two companies share the operation (the information shown is not complete).

 PREFEITURA MUNICIPAL DE CURITIBA  URBS - URBANIZAÇÃO DE CURITIBA S.A							
ÁREA DE OPERAÇÃO DO TRANSPORTE COLETIVO							
UNIDADE DE ESTUDOS E CONTROLE							
Data Base: 07/11/2016							
Período: 11/2016							
DADOS OPERACIONAIS - RIT - DIAS ÚTEIS - NOVEMBRO - 2016							
Código Empresa	Nome Empresa	Código Linha	Nome Linha	Tipo Veículo	Categoria Serviço	Tab	Km Tabela + 6
07	REDENTOR/TRANSBUS	550	LIGEIRÃO - PINHEIRINHO / C. GOMES	BIARTICULADO BIO	LIGEIRÃO	001	83.156
07	REDENTOR/TRANSBUS	550	LIGEIRÃO - PINHEIRINHO / C. GOMES	BIARTICULADO BIO	LIGEIRÃO	001	59.842
07	REDENTOR/TRANSBUS	550	LIGEIRÃO - PINHEIRINHO / C. GOMES	BIARTICULADO BIO	LIGEIRÃO	002	428.995
07	REDENTOR/TRANSBUS	550	LIGEIRÃO - PINHEIRINHO / C. GOMES	BIARTICULADO BIO	LIGEIRÃO	003	83.156
07	REDENTOR/TRANSBUS	550	LIGEIRÃO - PINHEIRINHO / C. GOMES	BIARTICULADO BIO	LIGEIRÃO	003	59.842
07	REDENTOR/TRANSBUS	550	LIGEIRÃO - PINHEIRINHO / C. GOMES	BIARTICULADO BIO	LIGEIRÃO	004	59.323
07	REDENTOR/TRANSBUS	550	LIGEIRÃO - PINHEIRINHO / C. GOMES	BIARTICULADO BIO	LIGEIRÃO	004	59.842
07	REDENTOR/TRANSBUS	550	LIGEIRÃO - PINHEIRINHO / C. GOMES	BIARTICULADO BIO	LIGEIRÃO	012	405.162
07	REDENTOR/TRANSBUS	550	LIGEIRÃO - PINHEIRINHO / C. GOMES	BIARTICULADO BIO	LIGEIRÃO	013	59.323
07	REDENTOR/TRANSBUS	550	LIGEIRÃO - PINHEIRINHO / C. GOMES	BIARTICULADO BIO	LIGEIRÃO	015	428.995
07	REDENTOR/TRANSBUS	550	LIGEIRÃO - PINHEIRINHO / C. GOMES	ARTICULADO 20	LIGEIRÃO	016	41.767
11	SORRISO/PIONEIRO	550	LIGEIRÃO - PINHEIRINHO / C. GOMES	BIARTICULADO BIO	LIGEIRÃO	005	357.496
11	SORRISO/PIONEIRO	550	LIGEIRÃO - PINHEIRINHO / C. GOMES	BIARTICULADO BIO	LIGEIRÃO	006	59.323
11	SORRISO/PIONEIRO	550	LIGEIRÃO - PINHEIRINHO / C. GOMES	BIARTICULADO BIO	LIGEIRÃO	006	59.842
11	SORRISO/PIONEIRO	550	LIGEIRÃO - PINHEIRINHO / C. GOMES	BIARTICULADO BIO	LIGEIRÃO	007	428.995
11	SORRISO/PIONEIRO	550	LIGEIRÃO - PINHEIRINHO / C. GOMES	BIARTICULADO BIO	LIGEIRÃO	008	59.323
11	SORRISO/PIONEIRO	550	LIGEIRÃO - PINHEIRINHO / C. GOMES	BIARTICULADO BIO	LIGEIRÃO	008	59.842
11	SORRISO/PIONEIRO	550	LIGEIRÃO - PINHEIRINHO / C. GOMES	BIARTICULADO BIO	LIGEIRÃO	009	83.156
11	SORRISO/PIONEIRO	550	LIGEIRÃO - PINHEIRINHO / C. GOMES	BIARTICULADO BIO	LIGEIRÃO	009	59.842

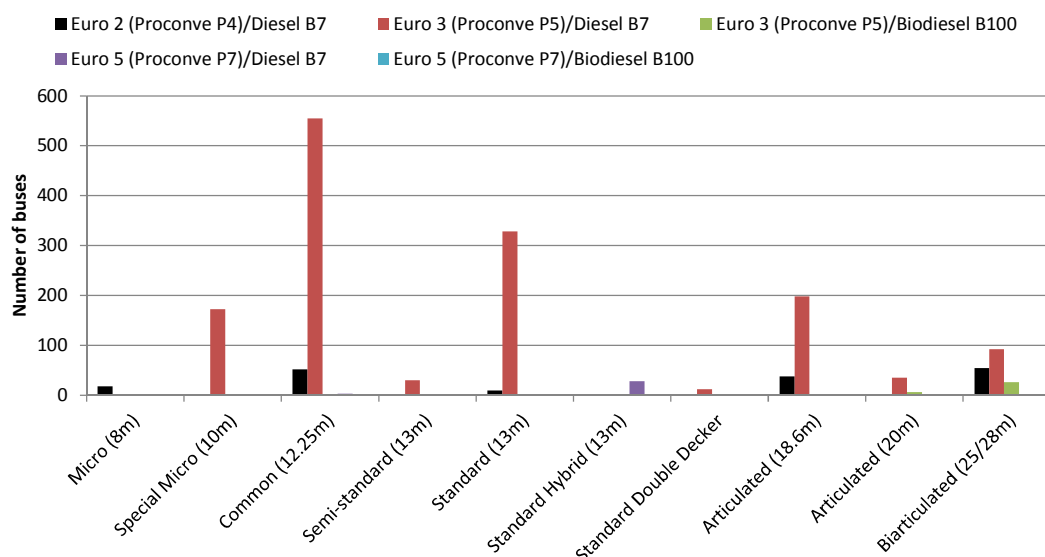


Fig 3.4.3 Distribution of different bus technologies in Curitiba. In total 1660 buses are in operation.

Table 3.4.2 Emission factors used for public transport taken from the European model HBEFA. For micro HBEFA buses <15 ton were used, for standard HBEFA 15-18 ton and for articulated buses HBEFA >18 ton, considering signed 50 km/h and saturated traffic conditions (courtesy to Lars Burman at Stockholm municipality, providing HBEFA data). The emission factors for bi-articulated buses were extrapolated using Curitiba information on fuel consumption.

	technology	NOx	PM exhaust		BC		fuel cons.
		(mg/veh,km)	diesel	biodiesel	diesel	biodiesel	
micro	Euro II	9840	184	92	120	60	326
standard	Euro II	13080	264	132	172	86	444
articulated	Euro II	16380	373	187	242	121	568
biarticulated	Euro II	19438	443	221	288	144	698
micro	Euro III	9020	171	86	120	60	344
standard	Euro III	11740	237	119	166	83	463
articulated	Euro III	14770	285	143	200	100	588
biarticulated	Euro III	17527	338	169	237	118	698
micro	Euro V	6690	52	26	39	20	298
standard	Euro V	8370	68	34	51	26	410
articulated	Euro V	7750	81	41	61	30	535
biarticulated	Euro V	9197	96	48	72	36	634

Private transport emissions

In order to achieve consistent data for the entire city, we have used a model output from the VISSIM model provided by IPPUC. The output data provides morning and afternoon peak hour volume flows of three vehicle types: cars, utility (treated as diesel-fueled light duty) vehicles, and trucks. Fleet composition of the cars was taken from DETRANPR data from 2016, indicating 6% cars running on ethanol, 51% flex-fuel cars

running on gasoline and 43% gasoline cars. Based on traffic regulations for heavy duty traffic, we have assumed three types of fleet composition for the private transport:

- Inner city (inside the ring road): 93% cars, 5% utility and 2% trucks
- Transit roads open for heavy duty (BR-476 and BR-277): 82% cars, 8% utility and 10% trucks
- Ring road: 59% cars, 9% utility and 32% trucks

The time variation of the traffic was taken from speed radar data, but synthesized to temporal variations for different days of the week (Fig. 3.4.3).

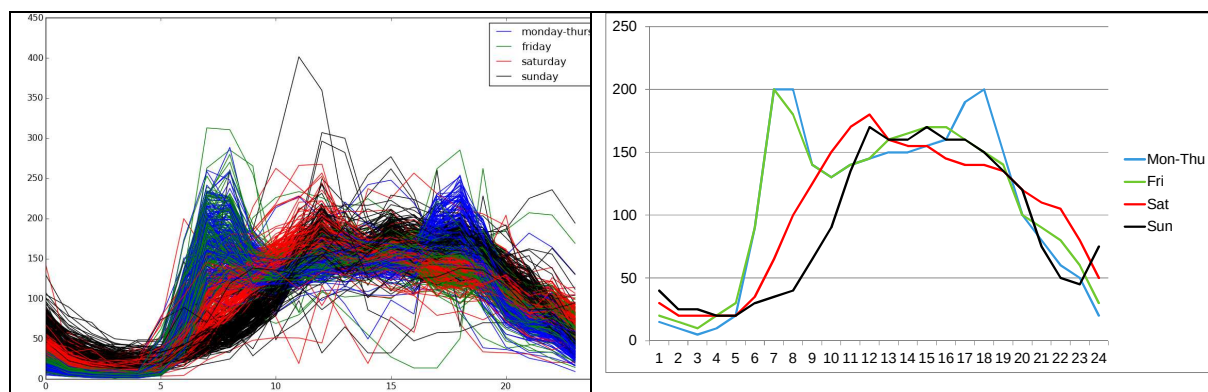


Figure 3.4.3 Measured traffic volumes from the so called speed traps (speed radar data) at 230 locations. To the left raw data, to the right aggregated time variations for different parts of the week. The temporal variations, as shown to the right, have been normalized for the dispersion simulations.

Emission factors were taken from the European Environmental Agency (EEA) handbook:

<http://www.eea.europa.eu/publications/emep-eea-guidebook-2016/part-b-sectoral-guidance-chapters/1-energy/1-a-combustion/1-a-3-b-i/view>

with Tier 2 exhaust emission factors from Table 3-17 and 3-18 of this handbook. The split of PM_{2.5} into BC and other components were taken from Table 3-117 in the same publication. Given the large uncertainties in the spatial distribution of traffic volume and fleet composition data, a simplified approach was used for the emission factors. The technical characteristics of the Curitiba fleet were set to meet Euro 4 standards for cars and light duty vehicles (at least 60% of the fleet corresponds to this technology). For heavy duty vehicles, Euro 3 was assumed for all vehicles, although a considerable fraction of the heavy duty vehicles have both older and more modern technologies. We also selected one size to represent each vehicle type, for cars 1.4-2.0 liters engine, for light duty diesels a weight <3.5 tons and for heavy duty diesels a weight 16-32 tons. Table 3.4.3 documents the emission factors used. Cars using ethanol and gasoline were assumed to emit the same.

Table 3.4.3 Emission factors used for private vehicles (from EEA, 2016).

	NO_x	PM	BC	fuel cons.
	(mg/veh,km)	(mg/veh,km)	(mg/veh,km)	(ml/veh,km)
Cars	61	1	0.15	115
LDV <3 tons	831	41	36	95
HDV 16-32 tons	6270	130	91	250

For the street canyon modeling along the biking routes (see Fig. 3.3.2 in the previous section), we used manually estimated traffic volumes from speed trap data and experiences from traffic modelling at IPPUC.

Residential emissions

There is no existing georeferenced database of residential heating/cooking facilities and techniques and the ParCur project has not had resources to develop a new inventory. Instead we will look for possible impacts not explained by the sources that form part of the emission inventory, possibly relating them to residential wood or waste combustion.

Persons residing in Curitiba have indicated that there are few residential houses in the city that use wood or coal combustion for heating or cooking on a daily basis, although there is a use of outdoor barbecuing that takes place mostly on weekends. However, in the city periphery there may be some use of wood stoves for heating purposes.

Restaurants

Through UTFPR, the ParCur project got access to a list of names of 1061 restaurants located in Tatuquara, Centro and Batel districts (Fig. 3.4.4). Analyzing the information and identifying their location through Google Maps, we considered it too incomplete to be the basis of an emission inventory. During this phase of ParCur we worked with restaurant emissions as a possible, but not quantified, source of PM and BC.

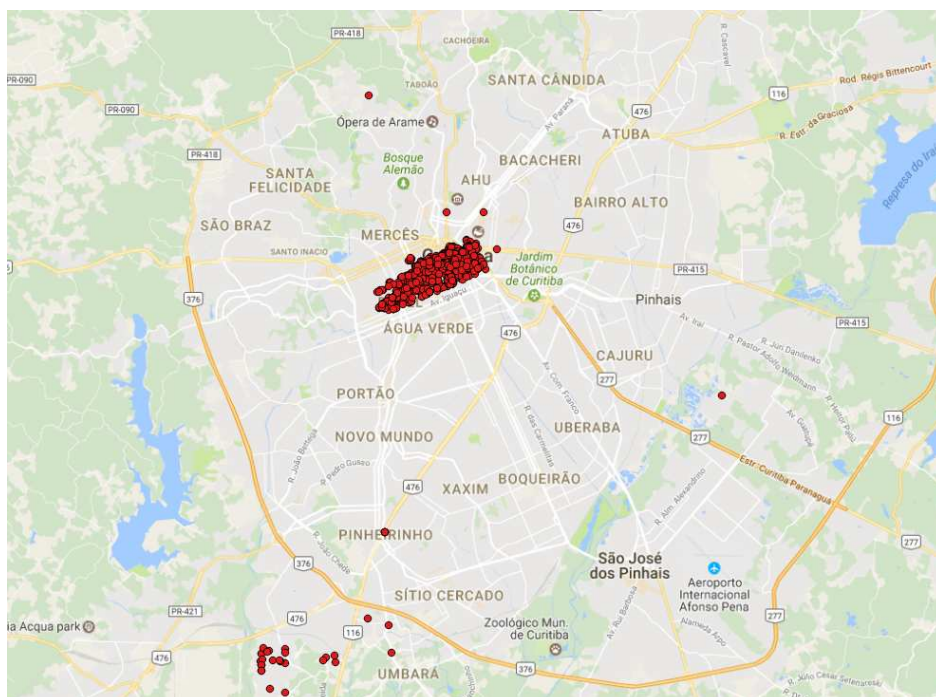


Figure 3.4.4 Restaurants listed with names, locations found through Google map (only Tatuquara, Centro and Batel districts).

Emissions outside Curitiba, used as input to the regional scale model

The emission pre-processor (PREP-CHEM-SRC, Freitas et al., 2011) provides emission fields interpolated to serve as input to regional and global transport models and considers urban/industrial, biogenic, biomass burning and volcano sources. The biomass burning sources for carbon monoxide (CO), carbon dioxide (CO₂), methane (CH₄) and NO_x and PM_{2.5}) can be estimated directly from satellite remote sensing fire detections using the Brazilian Biomass Burning Emission Model (3BEM, Longo et al., 2009). The organic and black carbon, are obtained from the EDGAR HTAP (<http://edgar.jrc.ec.europa.eu>, Olivier et al., 1996, 1999) and 3BEM model.

The urban emissions are provided from a South America regional inventory that aggregates local inventories vehicular emissions with RETRO (<http://retro.enes.org>) and EDGAR v4 (<http://edgar.jrc.ec.europa.eu>, Olivier et al., 1996, 1999) anthropogenic global database (Alonso et al., 2010). Industrial and road transport emissions from the IAP inventory were included for Paraná State (Table 3.4.4).

Table 3.4.4 Emissions sources databases used in PREP-CHEM-SRC.

Species	Source
Anthropogenic gases	South America inventory (Alonso et al, 2010) updated with IAP inventory to Paraná state (industrial and transport sources for CO and NO _x).
Biomass burning gases	3BEM model (Longo et al., 2009)
Anthropogenic PM _{2.5} and PM ₁₀	South America inventory (Alonso et al, 2010) updated with IAP inventory to Paraná state (PM _{2.5} /PM ₁₀ = 0.7)
Biomass burning aerosols (PM _{2.5} , PM ₁₀ , OC and BC)	3BEM model (Longo et al., 2009)
Anthropogenic OC and BC	EDGAR HTAP (edgar.jrc.ec.europa.eu/htap.php)

3.5 Regional dispersion modeling

With the aim of simulating the background influence of fires, urban plumes from nearby cities and long-range transported pollutants, a numerical experiment covering the campaign period was performed with CCATT-BRAMS version 5 (Freitas et al., 2017), using emissions from PREP-CHEM-SRC without the Curitiba city contribution.

The CCATT-BRAMS modeling system consists of an atmospheric chemistry transport model (CCATT) coupled on-line with a limited-area atmospheric model (BRAMS). The BRAMS model is the Brazilian version (with specific development for the tropical and

subtropical regions) of the non-hydrostatic time-split compressible model RAMS (Regional Atmospheric Modeling System), developed at the University of the State of Colorado (Tripoli and Cotton, 1982).

The CCATT is an Eulerian model of atmospheric transport that simulates the trace gases mixing rate through the solution of the mass conservation equation, which includes advection, turbulent mixing in the planetary boundary layer, dry and wet deposition, ascension plume associated with fires, and vertical transport associated with shallow (not precipitant) and deep convection. In addition, the model includes chemical reactions and aerosol processes, solar radiation and terrestrial interactions.

The transport of pollutants by convection in the model CCATT-BRAMS uses the formalism of mass flow, based on Grell and Devenyi (2002) deep convection scheme, which accounts for the mass transport in the updrafts and downdrafts (only deep convection) within the cumulus cloud and the environmental subsidence. There are two important updates in the last versions: the introduction of a monotonic formulation (Walcek, 2000) for the advective transport, as an additional option to the second order scheme proposed by Tremback (1987) and the use of observational information from AERONET (Aerosol RObotic NETwork) as input to calculate the optical properties required by the Community Aerosol and Radiation Model for Atmosphere (CARMA) included in the model (Longo et al., 2013; Rosario et al., 2011, 2013).

The CCATT-BRAMS can be configured with any chemical mechanism, using the M-SPACK pre-processor (Modified Simplified Preprocessor for Atmospheric Chemical Kinetics) (Djouad, 2002; Longo et al., 2013). The M-SPACK automatically pre-processes the chemical species aggregation and creates the Fortran90 routine files to use in the model. There are two options for the rates of photolysis: standard conditions from lookup tables or updated at each timestep using the model FAST-TUV (Tie et al., 2003). The numerical integrator of chemical mechanisms is based on the Rosenbrock method. The simulations performed in this work use the RODAS 3 version, with four stages and third order, described in Freitas et al. (2017) and RELACS chemical mechanism (Crassier et al., 2000).

Figure 3.5.1 shows the selected grids and Figure 3.4.2 shows the CO emissions on the second grid. The first simulation, with 50 km spatial resolution (G1 in Fig. 3.5.1, uses atmospheric initial and boundary conditions from T126L42 Global model (CPTEC/INPE – Brazil) and chemical initial and boundary conditions from MOCAGE (Josse et al., 2004; Teyssède et al., 2007), included in the model system by the DPREP-CHEM module. The output of the first simulation was used as boundary condition for the second experiment, with 10 km spatial resolution (G2 in Fig. 3.4.1).

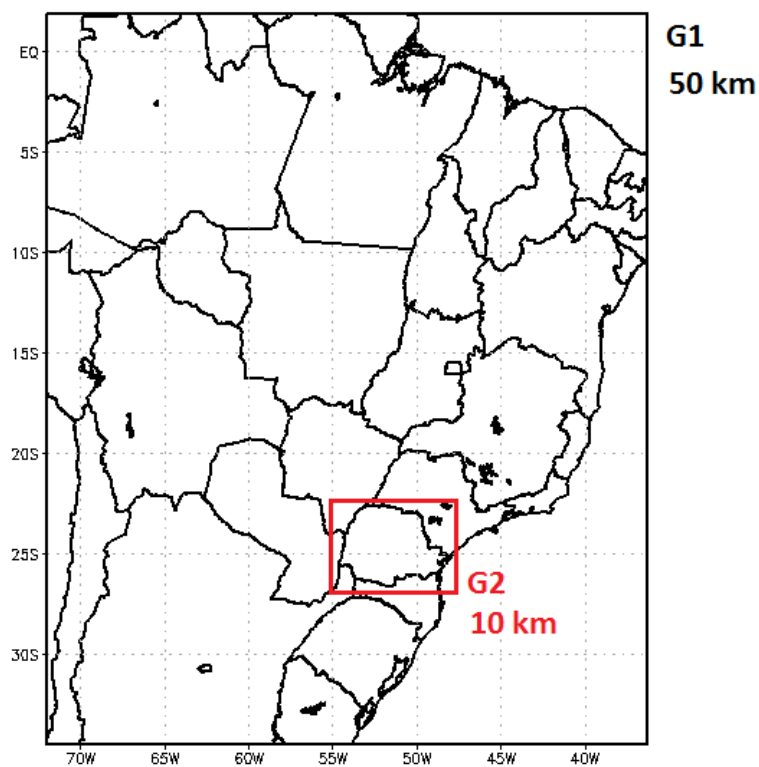


Figure 3.5.1 Simulations grids for the regional model.

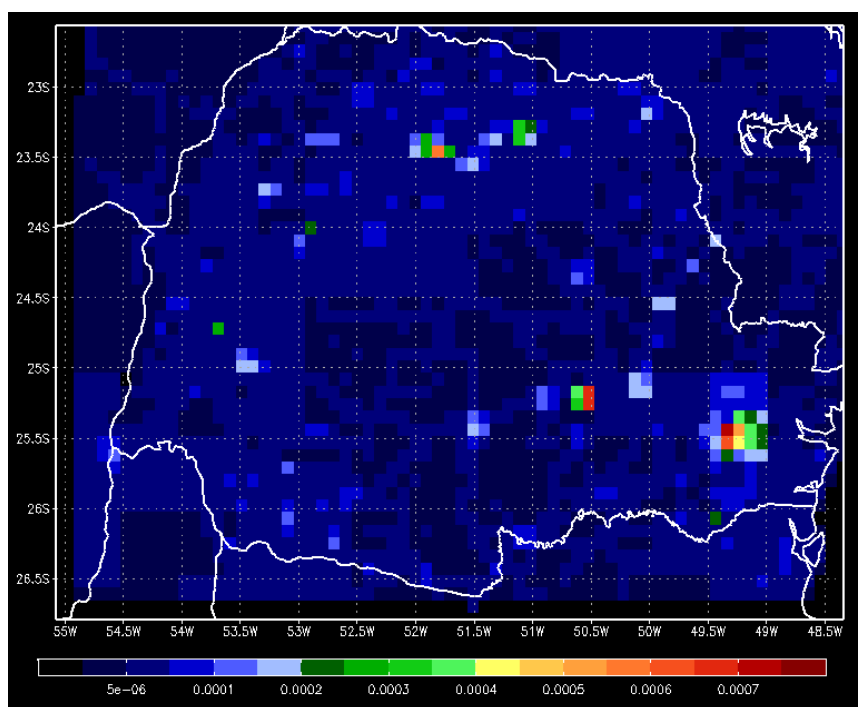


Figure 3.5.2 Carbon monoxide emission in the finer grid ($\text{kgm}^{-2}\text{day}^{-1}$)

3.6 Local dispersion modeling

Two types of dispersion modeling is used at the local scale, the first one being a Gaussian model used to simulate the spatially distributed impact of local emissions over Curitiba and its closer surroundings (model area 32x32 km²). ParCur also uses a semi-empirical street canyon model to simulate the impact of traffic inside a specific street canyon like, e.g., the Marechal Deodoro street where the monitoring station is located and the streets along the biking routes. Both models use meteorological information pre-processed in a wind model. The dispersion models and the wind model are part of the Airviro system (<http://www.smhi.se/airviro>). The implementation of Airviro for the Curitiba domain requires gridded data of topography and land use, including the typical height of the buildings in different areas (Fig. 3.6.1).

The wind field calculation is based on the concept first described by Danard (1976), where mesoscale winds are generated by using the horizontal momentum equation, the pressure tendency equation and the first thermodynamic equation. This concept assumes that small-scale winds can be seen as a local adaptation of large scale winds (free winds) due to local fluxes of heat and momentum from the sea or earth surface.

The large-scale winds, as well as vertical fluxes of momentum and temperature, are estimated from profile measurements in one (this is the case in Curitiba) or several meteorological masts. A free wind, i.e. a wind at the location of the mast at the level where it's not affected by surface fluxes of heat and momentum, is estimated based on the profile measurements and extrapolation procedures suggested by Holtslag (1984). When the free wind field is estimated, the initial surface pressure field is determined in accordance with a geostrophic balance.

The determination of turbulence scaling parameters like, e.g., the Monin-Obukhov length (L) follows the profile method discussed by Berkowicz and Prahm (1982). When vertical temperature gradient data are missing – as is the case for this Curitiba application – it is possible to determine the same scalars using ordinary synoptic data and the resistance method (van Ulden & Holtslag, 1985).

The Gaussian model simulates one hour average concentration plumes from multiple point sources, each one with an individual plume rise. Line sources (road traffic) are converted to a number of surface point sources along the line, where the initial dispersion is linked to traffic intensity and the turbulence created by the vehicles. In the city centre, the Gaussian model should calculate the concentrations at roof level, so also the height of the buildings will influence the initial dispersion (high buildings give possibility to a larger initial dispersion, as compared to an area with no buildings where simulated concentrations should represent ground level (2 m above ground). Fig. 3.6.1 and 3.6.2 show the model domain, the topography and the way the high buildings are distributed along the main transport corridors.

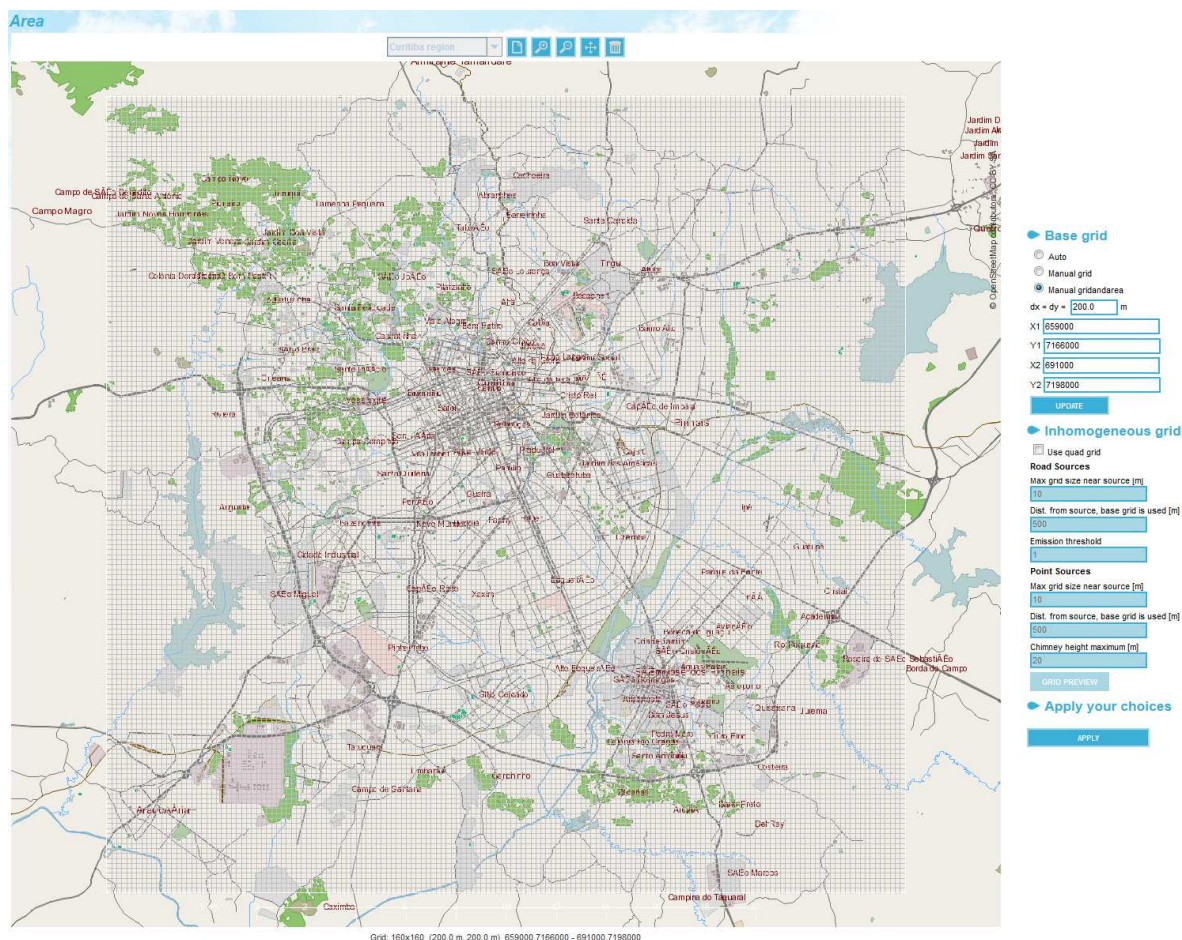


Figure 3.6.1 Modeling domain and spatial resolution for the wind model and the Gaussian dispersion model.

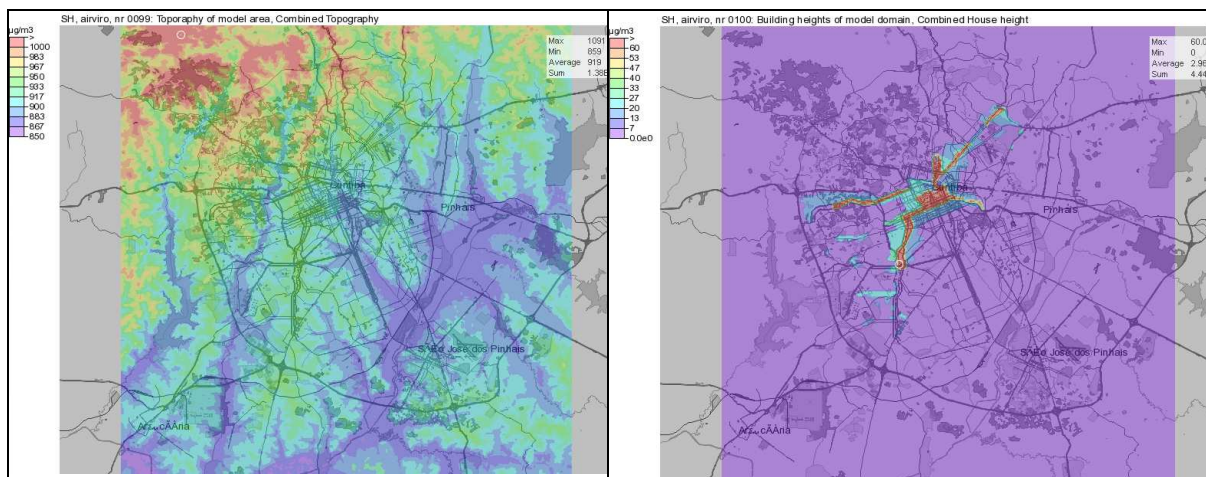


Figure 3.6.2 Topography and building heights within the 32x32 km² domain for the local model. The building heights are taken from IPPUC's zoning map of Curitiba.

To determine the impact on air pollutant concentrations caused by vehicle emission inside street canyons, we used the OSPM model (Berkowicz, 2000). The model requires the dimensions of the street canyon, expressed in road width, number of lanes, the width between the surrounding houses and heights of the surrounding

houses in 12 directional sectors. The OSPM model has one part, which is a direct plume model, following the estimated wind direction at the bottom of the street canyon. The other part, taking care of the contribution from the recirculation, is calculated by a simple box model. OSPM assumes atmospheric stability conditions inside the street canyon to be neutral. The two receptor points are located at each side of the road and in the middle of the block (road link), i.e. they express the concentration levels at the pavement caused by local traffic. The contribution from the urban background, as well as from the long-range transported pollution arriving to the city, must be added to the OSPM output to obtain the actual concentration at the street canyon.

4 Results

4.1 Meteorological conditions in Curitiba

To match the NO_x sampling period, we report on the weather conditions between the 29th of July and the 12th of August and between the 15th and the 29th of August 2016. In the first period, a total of 32.7 mm of rainfall was registered in Curitiba, concentrated on the 8th and 9th of August (Fig. 4.1.1). In the second period, the rainfall amounted to 130.1 mm, with the largest amount (39.6 mm) on August 21st. According to the National Institute of Meteorology (INMET), the total amount of rainfall surpassed the expected 73.4 mm for a regular month of August in Curitiba.

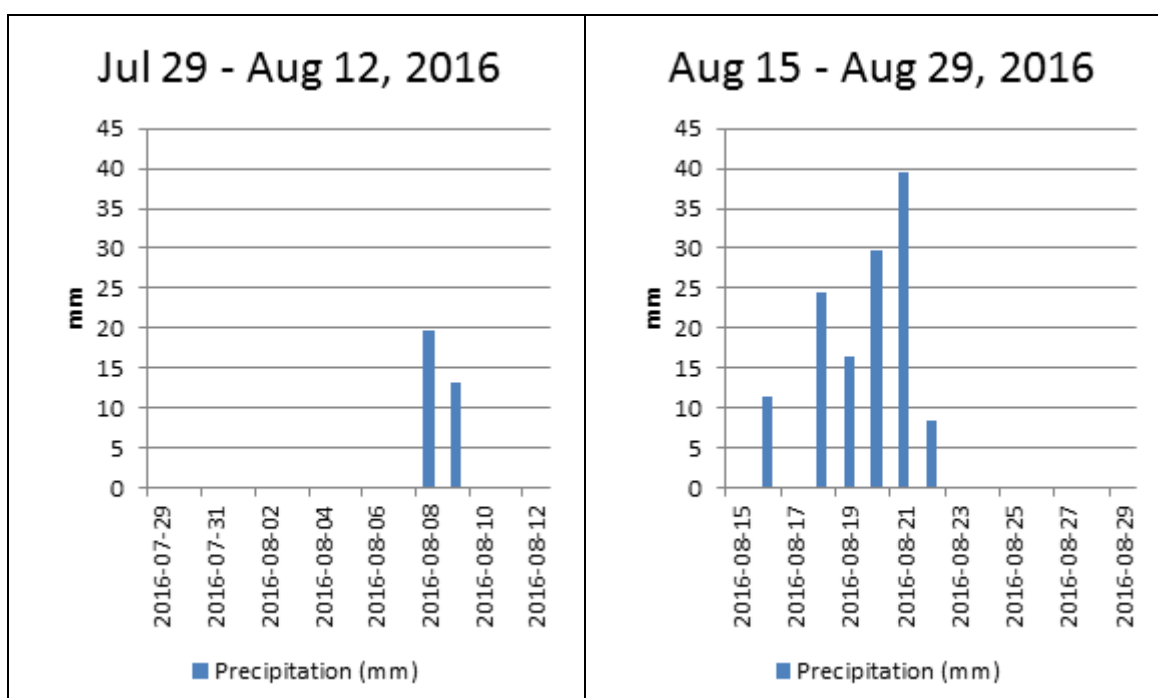


Figure 4.1.1 Precipitation levels registered during the ParCur monitoring campaign (INMET, 2016)

Northeasterly and easterly winds prevailed in the first period, with modest contributions from the west, south and northwest sectors. Northeasterly winds prevailed also in the second period, with about 10% contribution from the northwest sector. When winds turned to northwesterly direction, the wind intensity was somewhat stronger (above 4 m/s).

According to a recent study (to be published, Castelhana and Roseghini, 2017), the usual wind dynamics in this period of the year reveals winds mostly from east and northeast, with low frequency from other directions (Fig. 4.1.3).

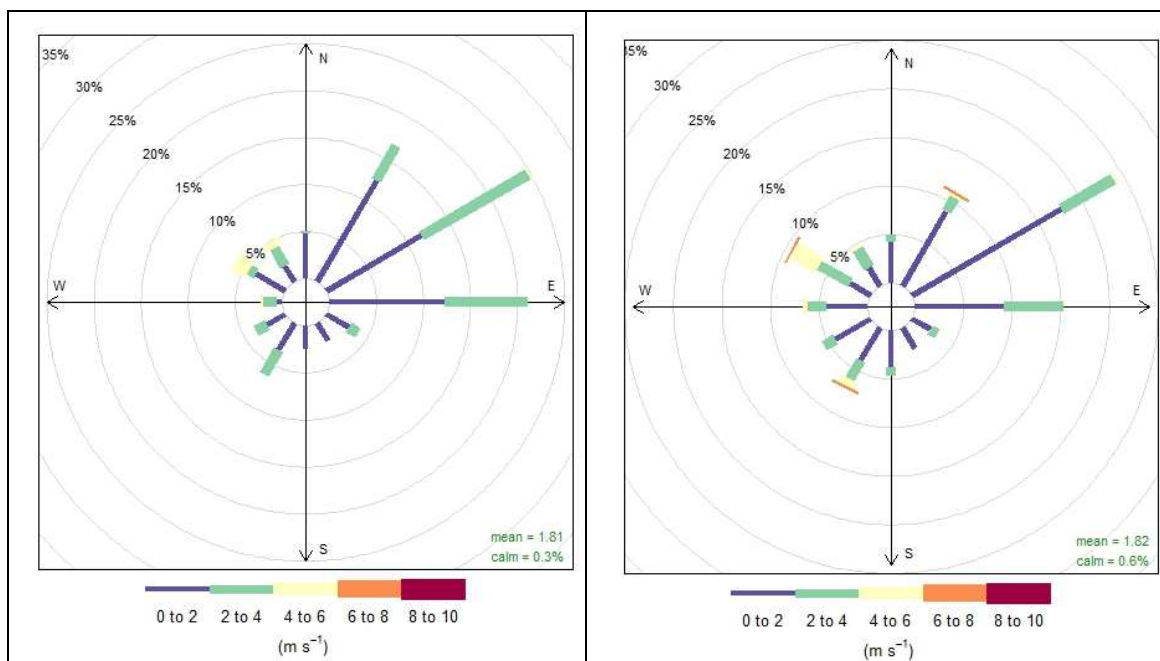


Figure 4.1.2 Wind speed and direction in Curitiba for the periods of 29/07 to 12/08 (left) and 15/08 to 29/08, 2016 (right).

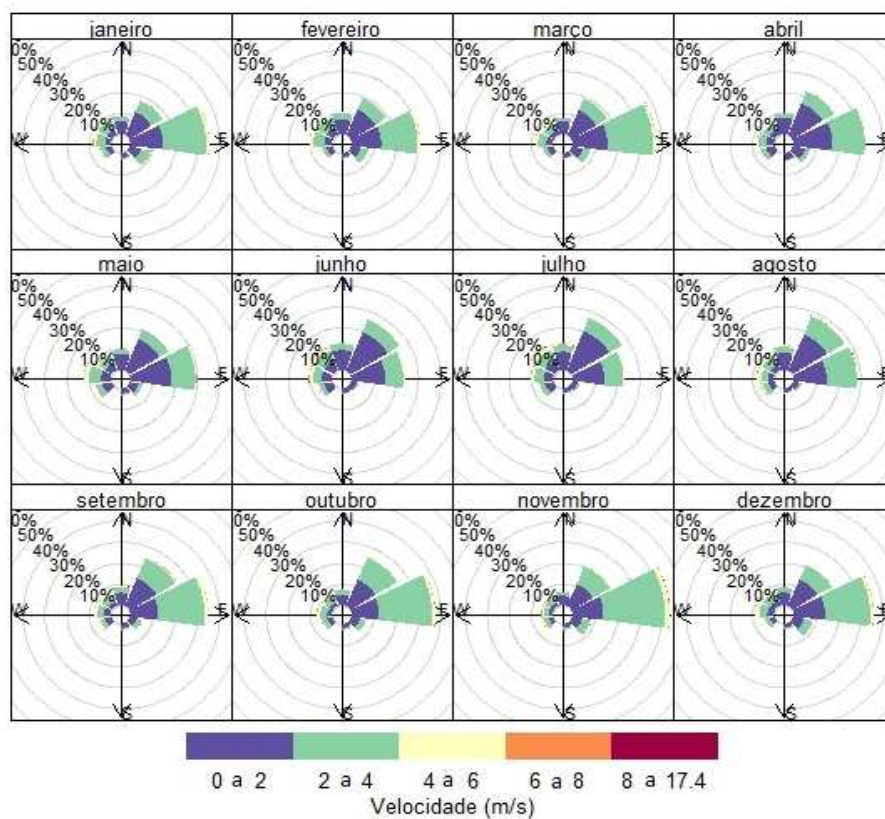


Figure 4.1.3 Wind speed and direction for Curitiba by month, period 2004 - 2015.

4.1.4 shows the average air temperature during the ParCur sampling campaign. The mean temperature (14.6 °C) was higher than the historical mean in the period 1991–2010 (14.1 °C). The highest daily value registered during the period was 20.4°C on the 29th of August and the lowest value was 8.6 °C on the 22nd of August.

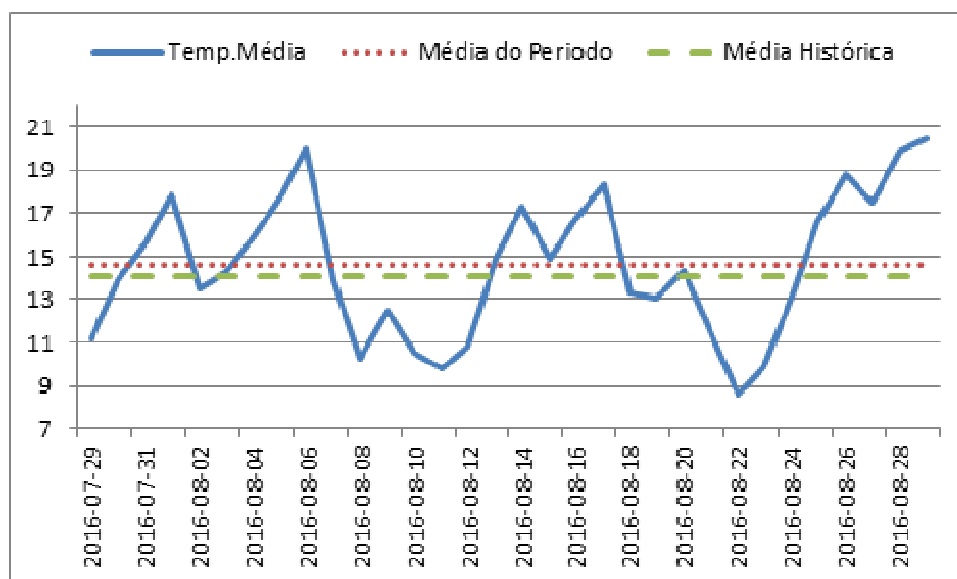


Figure 4.1.2 Daily average temperature (blue) during ParCur field campaign. Also mean temperatures during the monitoring campaign period in 2016 (red dotted) and the corresponding historical mean temperature for this season (green broken line).

4.2 Air Quality monitoring results

IAP monitoring network

The IAP operational monitoring stations of most interest for assessing PM₁₀ and NO₂/NO_x concentrations in Curitiba are Praça Ouvidor Pardini (IAP_PAR), Boqueirão (IAP_BOQ), Santa Cândida (IAP_STC) and Cidade Industrial (IAP_CIC). The analysis presents results from the period 2013-2015. We also compare the levels registered during the monitoring campaign (from the 25th of July to the 25th of August, 2016) with the levels obtained during the three preceding years 2013-2015. References are also the Brazilian air quality standards (limit values), the EU air quality directive and the WHO guidelines, given in Table 4.2.1.

Table 4.2.1 Limit values and WHO guidelines for PM₁₀, PM_{2.5} and NO₂ (µg/m³)

	PM10 annual	PM10 daily	PM2.5 annual	NO ₂ annual
Brazilian legislation	50	150	-	100
EU air quality directive	40	50*	25	40
WHO guidelines	20	50	10	40

*expressed as 90th percentile

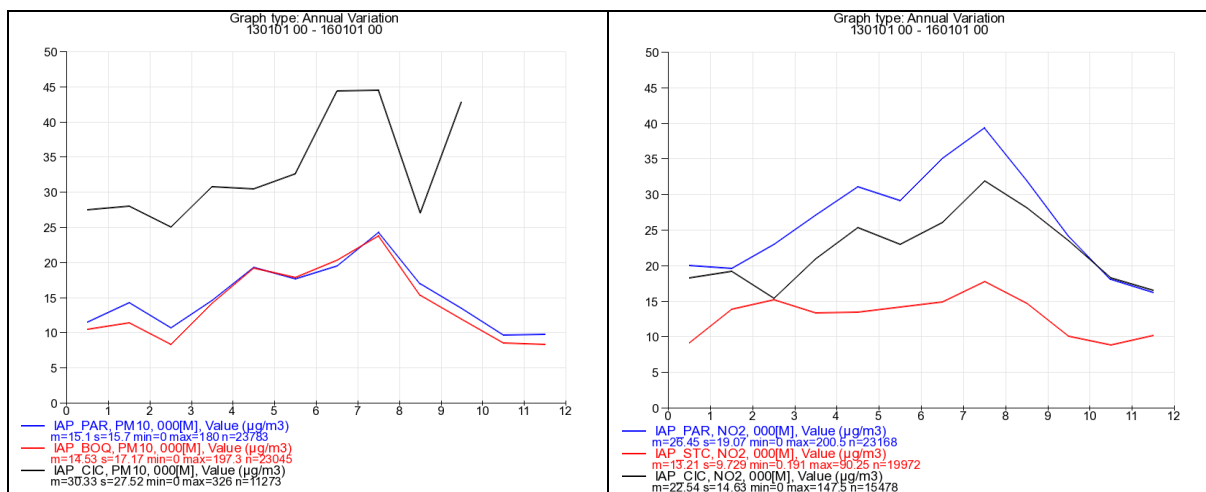


Figure 4.2.1 Monthly average levels of PM₁₀ (left) and NO₂ (right) from the IAP network during the period 2013-2015. Note that there are large data gaps at station IAP_CIC, especially for PM₁₀.

Air pollution levels in Curitiba are the highest in August, which motivated the campaign to be performed during this period of the year (Fig. 4.2.1). For PM₁₀ the levels are very similar between IAP_PAR and IAP_BOQ, which indicates that this pollutant is fairly homogeneous over the city. The PM₁₀ levels inside the city are well below the Brazilian standards and also below WHO guidelines. The PM₁₀ levels at IAP_CIC, located in the Cidade Industrial de Curitiba and also closer to the industrial area of Araucária towards south-southwest, are typically twice as high, although still below the Brazilian limit value for the annual average.

The highest NO₂ levels are found in the city center at IAP_PAR, which is situated close to a trafficked road. The NO₂ levels in IAP_CIC show a very similar seasonal variation as in IAP_PAR, indicating that both are influenced by NO_x emissions from traffic. The much lower levels registered at IAP_STC, located in the northeast periphery of the city, can be explained by this station to be situated further away from trafficked roads. It also represents a part of the city where the prevailing northeast wind brings in more clean air from the rural area, an air which has only passed over some residential areas before reaching the monitor. The NO₂ annual average levels registered in the IAP network are well below the Brazilian limit value and also below the WHO guidelines.

As illustrated in Fig. 4.2.2, PM₁₀, NO₂ and NO_x show daily variations with one peak in the morning and a second one in the evening or night.

For NO₂ and NO_x we can be rather sure that the dominating source in all stations is traffic, and its impact on the concentrations will depend on the dilution effect of the wind, which is stronger during midday. The impact of the long-range transported background NO₂ concentrations arriving to Curitiba is not in the same way affected by wind speed, however their contribution is lower than what is caused by local sources.

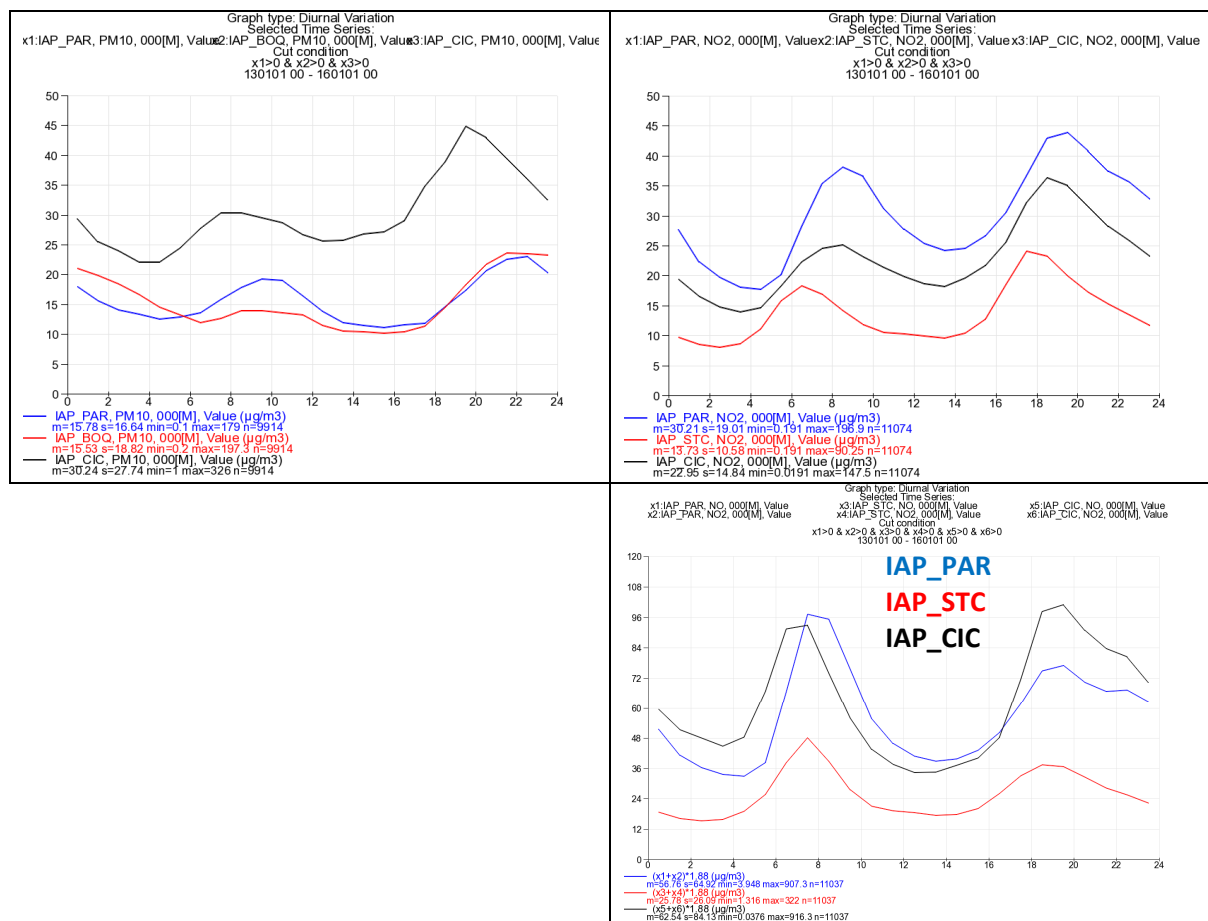


Figure 4.2.2 Daily variation in PM₁₀ (top, left), NO₂ (top, right) and NO_x (bottom, right) levels as registered in the IAP network during 2013-2015. To improve the comparison, only simultaneous valid data were included.

For PM₁₀ the long-range transported contribution is relatively higher than for NO₂ and NO_x, as indicated by the relatively smaller diurnal variations in comparison to mean levels. For IAP_CIC the daily variation of PM₁₀ is fairly similar to that for NO₂, so the dominating local source is likely traffic or an activity that has the same temporal variation as the traffic in this zone. The PM₁₀ peaks in the IAP_PAR and IAP_BOQ areas come later, especially the second one that rises up late at night, indicating some important activities other than transport.

Table 4.2.2 Average levels during the period 25th July to 24th August, for the three years 2013-2015 and for the monitoring campaign period in 2016 (µg/m³)

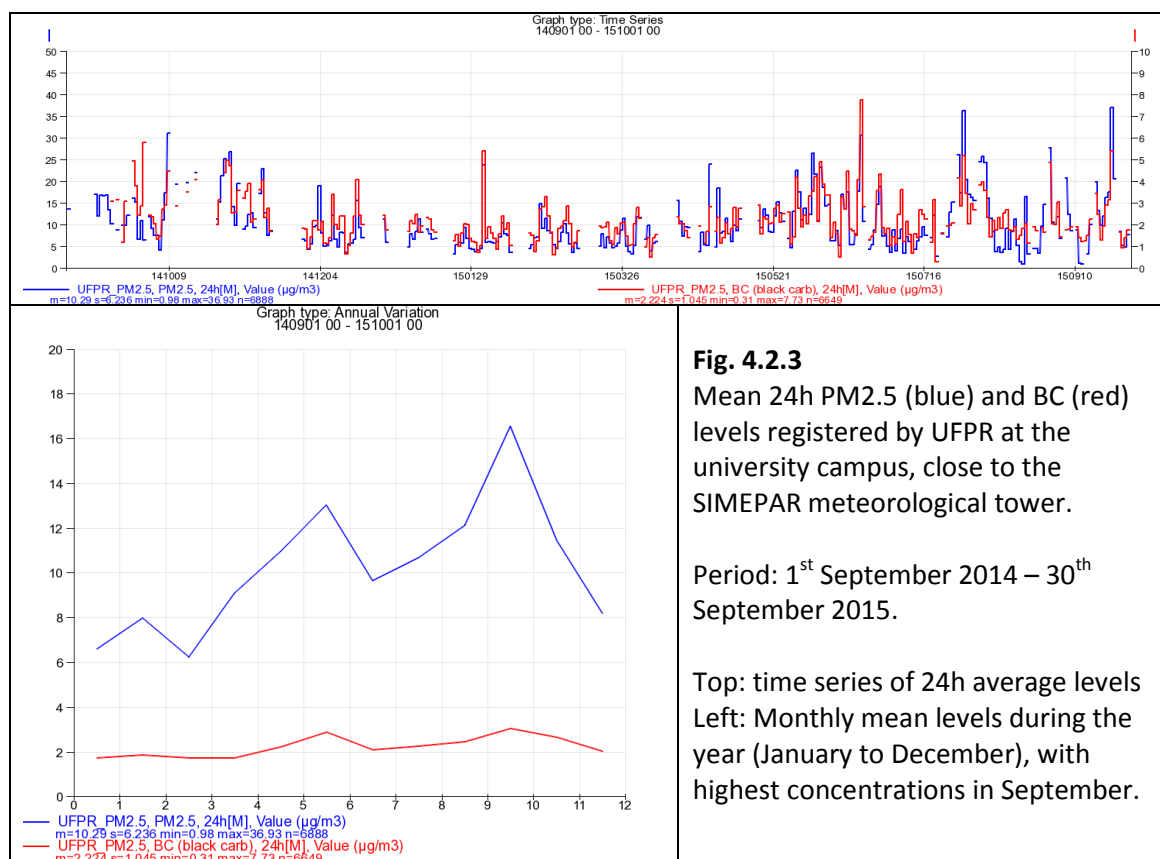
	PM ₁₀ IAP_PAR	PM ₁₀ IAP_BOQ	NO ₂ IAP_PAR	NO ₂ IAP_STC	NO _x IAP_PAR	NO _x IAP_STC
2013-2014-2015	23.3	23.6	37.7	17.4	86.5	34.3
2016	17.0	12.1	18.3	14.9	43.0	30.0
% difference 2016 compared to historical data	-27%	-49%	-51%	-14%	-50%	-13%

Table 4.2.2 shows a rather large difference in the registered levels in the IAP monitoring network between the month-long monitoring campaign and the corresponding monthly periods during the three preceding years. All variables, PM₁₀, NO₂ and NO_x, were considerably lower during the monitoring campaign, as compared to the historical conditions. Since anthropogenic emissions are normally varying slowly from year to year, it is most likely that the meteorological conditions were more favorable – in the sense that they favored the dilution – during the campaign period of 2016, as compared to the conditions during the winters of the historical period of 2013-2016. The high precipitation amount occurred during 2016, as compared to 2013-2015, likely had a role in reducing the PM₁₀ levels. There may also be differences in long-range pollution levels transported into Curitiba between the years.

UFPR PM_{2.5} and BC monitoring prior to ParCur

There are few historical PM_{2.5} and BC concentration data from Curitiba. One interesting data set was collected by UFPR from September 2014 to September 2015 at the university campus, close to the SIMEPAR meteorological station (see map in Fig. 3.3.1), about 100 m from the BR-277 highway. The monitor collected 24h averages, as shown in Fig. 4.2.3.

The PM_{2.5} mean level at this station was 10.3 µg/m³, with maximum daily levels rising to 35-40 µg/m³. BC levels measured with the aethalometer averaged to 2.2 µg/m³, with maximum daily values of 8 µg/m³ during traffic peak hours. Also brown carbon was registered, but with a much lower average levels <0.2 µg/m³ and with less pronounced daily variation.



PM and BC levels in the city centre, close to traffic

The BC measurements at the traffic station of Marechal Deodoro, registered at roof and street levels, are displayed in Fig. 4.2.4 (time series of hourly data) and Fig. 4.2.5 (daily variation). There is a pronounced daily variation with one morning peak and an afternoon peak. From the hourly data it can be seen that the street levels during the night sometimes – but not on average – drop to the same concentration level as at the roof. The average BC level is $2.3 \mu\text{g}/\text{m}^3$ at the roof and $5.5 \mu\text{g}/\text{m}^3$ at street level, leaving a contribution of $3.2 \mu\text{g}/\text{m}^3$ from the local traffic down on the street.

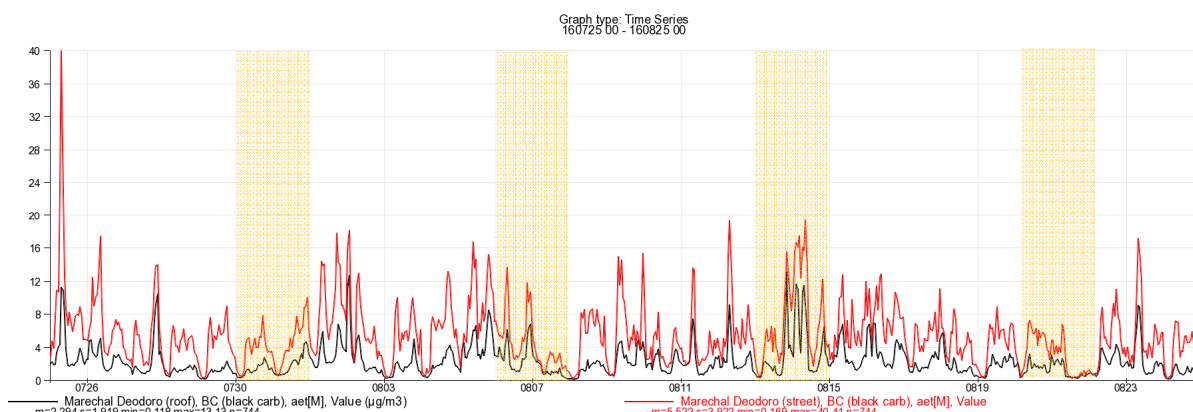
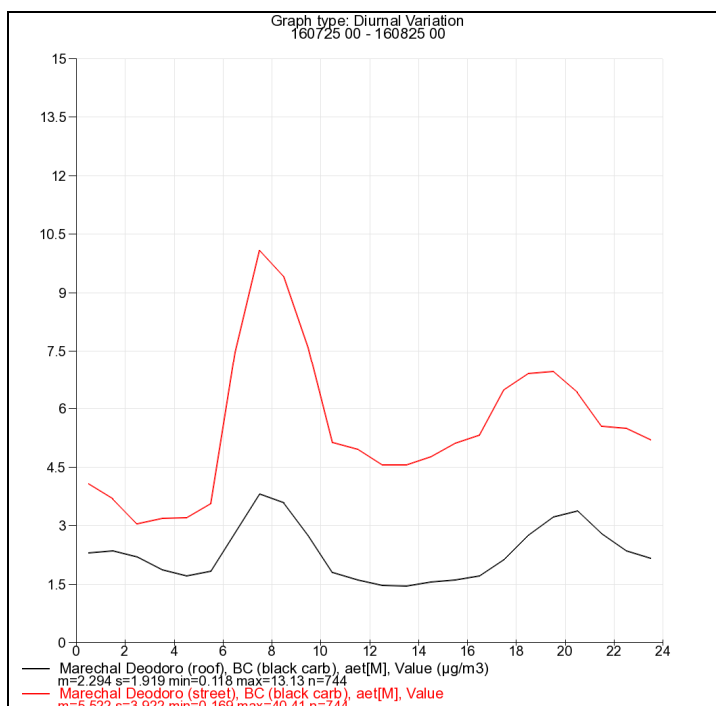


Figure 4.2.4 Hourly data of BC at Marechal Deodoro station, at roof level (black) and at street level (red). Unit: $\mu\text{g}/\text{m}^3$. Weekends marked in pink.

Figure 4.2.5 Daily variation of BC levels at Marechal Deodoro station, at roof level (black) and at street level (red). Unit: $\mu\text{g}/\text{m}^3$.



The BC levels obtained at Marechal Deodoro can be compared to two other street canyons (see Table 4.2.3). The results from Londrina confirm the importance of local traffic as the dominating source of BC. The levels in Stockholm some 10 years back (2006) are very similar to those presently found in Curitiba, but the results from 2013 illustrate the potential of controlling vehicle technologies. It is very likely that the

contribution of BC emissions from the vehicle fleet in Brazil could be equally lowered in a few years, following a more strict legislation of vehicle technologies.

Table 4.2.3 Comparison of street canyon roof and street level BC concentrations from Curitiba, Londrina and Stockholm.

	traffic volume (veh/day)	roof level ($\mu\text{g}/\text{m}^3$)	street level ($\mu\text{g}/\text{m}^3$)	references
Curitiba 2016 (roof at 70 m)	24 000	2.3	5.5	This study
Londrina 2014 (roof at 23 m)	10 500	0.9	2.6	Krecl et al. (2016)
Stockholm 2006 (roof at 20 m)	28 000	1.6	5.3	Krecl et al. (2015)
Stockholm 2013 (roof at 20 m)	28 000	0.4	1.1	Krecl et al. (2017)

As for the $\text{PM}_{2.5}$ monitoring, there were technical problems with the street level monitor. However, the mobile monitoring performed with bikes offers simultaneous data of both BC and $\text{PM}_{2.5}$ collected at Marechal Deodoro station and along this street. We could see a good correlation between the two variables and it was possible to show that a scaling up of three times the BC data simulated well the $\text{PM}_{2.5}$ time series. Assuming this relation between BC and $\text{PM}_{2.5}$ within the Marechal Deodoro street canyon, the $\text{PM}_{2.5}$ concentration was estimated as approximately $17 \mu\text{g}/\text{m}^3$ at street level due to the impact of local traffic (Fig. 4.2.6). At roof level, the mean $\text{PM}_{2.5}$ concentration was $7 \mu\text{g}/\text{m}^3$ during the monitoring campaign.

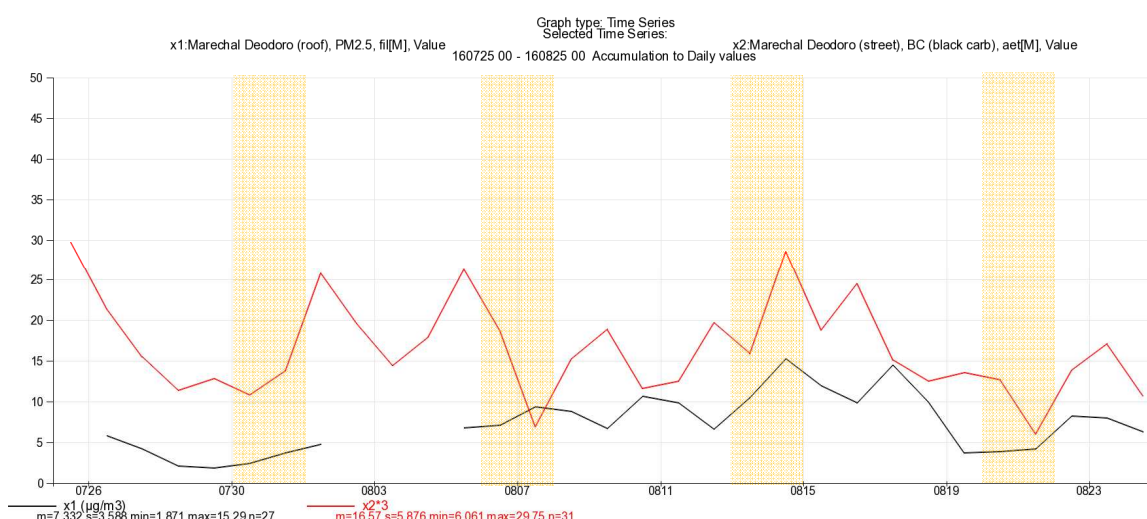


Figure 4.2.6 Daily $\text{PM}_{2.5}$ data at Marechal Deodoro station, at roof level (black) and at street level (red). Note that the street level $\text{PM}_{2.5}$ data has been reconstructed from the hourly BC data, applying a scale factor of 3 (factor taken from the simultaneous $\text{PM}_{2.5}$ and BC registered by the mobile monitors mounted on the bikes, which measured various times at the same location, such as the Marechal Deodoro station). Unit: $\mu\text{g}/\text{m}^3$. Weekends marked in pink.

PM and BC levels in a residential area

At Sítio Cercado station, a residential area in southern Curitiba some 800 m from the ring-road, we conducted measurements of PM_{2.5} (filter sampling of daily values, DustTrak hourly data), BC (micro aethalometer, hourly) and EC/OC (filter sampling of daily values, same as for PM_{2.5}). Results are presented in Figs. 4.2.7-8 and Table 4.2.4.

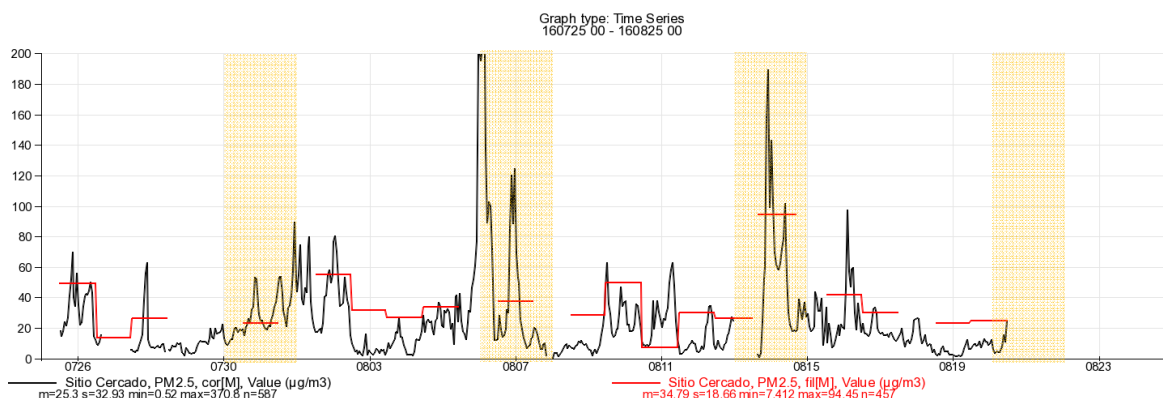


Figure 4.2.7 Daily PM_{2.5} (red, filter sampling) and hourly PM_{2.5} (black, Dusttrak) from Sítio Cercado station. Unit: $\mu\text{g}/\text{m}^3$. Weekends marked in pink.

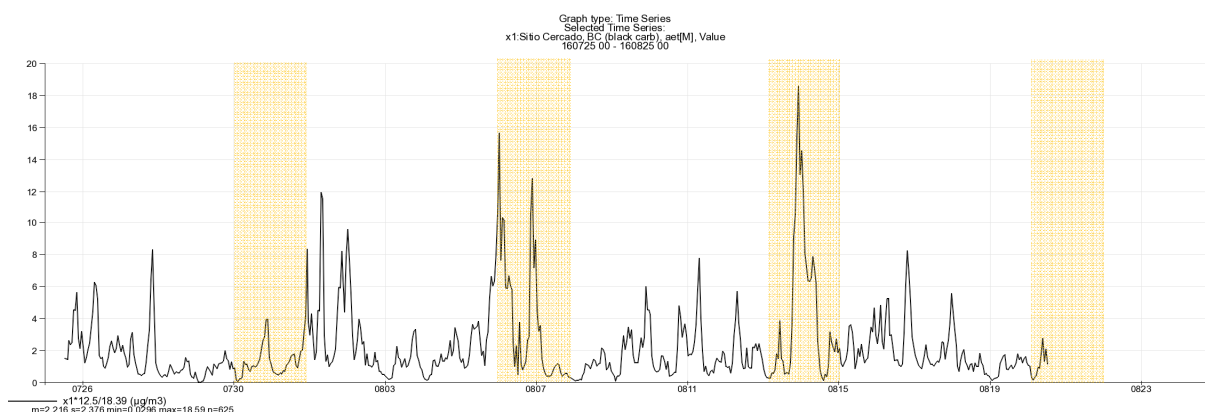


Figure 4.2.8 Daily BC (measured by the micro aethalometer) from Sítio Cercado station, after correction against EC analysis of filter samples (NIOSH protocol). Unit: $\mu\text{g}/\text{m}^3$. Weekends marked in pink.

Table 4.2.4 Mean levels of PM_{2.5}, EC and OC at Sítio Cercado during the period of the campaign, analyzed from daily filter samples.

	PM _{2.5}	EC	OC	Non-C
Average 17 daily samples ($\mu\text{g}/\text{m}^3$)	36.2	2.6	11.2	22.4
Percentage of PM _{2.5}	100%	7.1%	31.1%	61.8%

While BC mean levels in this residential area are very similar – in average about $2 \mu\text{g}/\text{m}^3$ – to those registered at roof level in the city center, as well as historically at the UFPR campus, the PM_{2.5} levels are much higher at the residential station of Sítio Cercado. In a traffic dominated environment, EC emissions are higher than OC. The high OC content at Sítio Cercado suggests other sources, likely wood/biomass combustion. In the Chilean city of Osorno the PM_{2.5} levels are mainly caused by emissions due to residential wood combustion and EC/OC fractions of PM_{2.5} were

reported as 2%-4% (EC) and 27%-34% (OC) (for more details see SMHI & CMMCh, 2015). Another assessment made in Saporanga, Southern Brazil, where also wood combustion was frequent, indicated 5%-8% (EC) and 29%-35% (OC), as reported by Gidhagen et al. (2015). Unfortunately, there are no EC/OC data available from the Marechal Deodoro roof level station at the city center, but one could expect a lower OC content there, as compared to Sítio Cercado. Note also the low brown carbon (which is assumed to contain large fractions of OC) levels registered by UFPR in 2014-2015, at a station close to the university campus.

Mobile monitoring of PM_{2.5} and BC

To analyze the spatial distribution of BC and PM_{2.5}, we defined polygons along the surveyed routes with lengths between 30 and 60 m. Then, all data points that fell into each individual polygon were used to calculate aggregated median concentrations of BC and PM_{2.5}. Aggregating the data to a fixed length interval is recommended to minimize the effects of extreme concentrations caused by sporadic vehicle exhaust emissions (Targino et al., 2016; 2017; Brantley et al., 2015). We calculated median concentrations because they are more representative measures of central tendency for non-normal distributed environmental data such as aerosol measurements. Figure 4.2.9 shows the spatial distribution of the aggregated median concentrations of BC (left) and PM_{2.5} (right) for all morning runs. It is possible to observe a large spatial variability for both variables. The BC concentrations were mostly between 4 and 8 $\mu\text{g}/\text{m}^3$, with some hotspots where concentrations surpassed 12.0 $\mu\text{g}/\text{m}^3$. The PM_{2.5} concentrations were also variable, especially across the north sector, and some hotspots coinciding with BC hotspots, as highlighted by the red rectangular area, where BC concentrations were above 16.0 $\mu\text{g}/\text{m}^3$ and PM_{2.5} above 28.0 $\mu\text{g}/\text{m}^3$ at some points. These hotspots usually occurred in areas with elevated number of vehicles, especially heavy duty vehicles. The traffic rate at the hotspot highlighted in Fig. 4.2.9 was 2469 vehicles/hour, of which 193 were buses and 25 were trucks.

The spatial distribution of PM_{2.5} within the south sector was not as variable, with values mostly between 21.0 and 28.0 $\mu\text{g}/\text{m}^3$, and hotspots with concentrations above 28.0 $\mu\text{g}/\text{m}^3$. As mentioned previously, the south sector has a speed limit of 60 km/h, whilst the north sector has a limit of 40 km/h. Thus, vehicles driving at higher speeds in the south sector may cause an increase of non-exhaust particles which contribute significantly to the mass of PM_{2.5}, but not to the mass of BC.

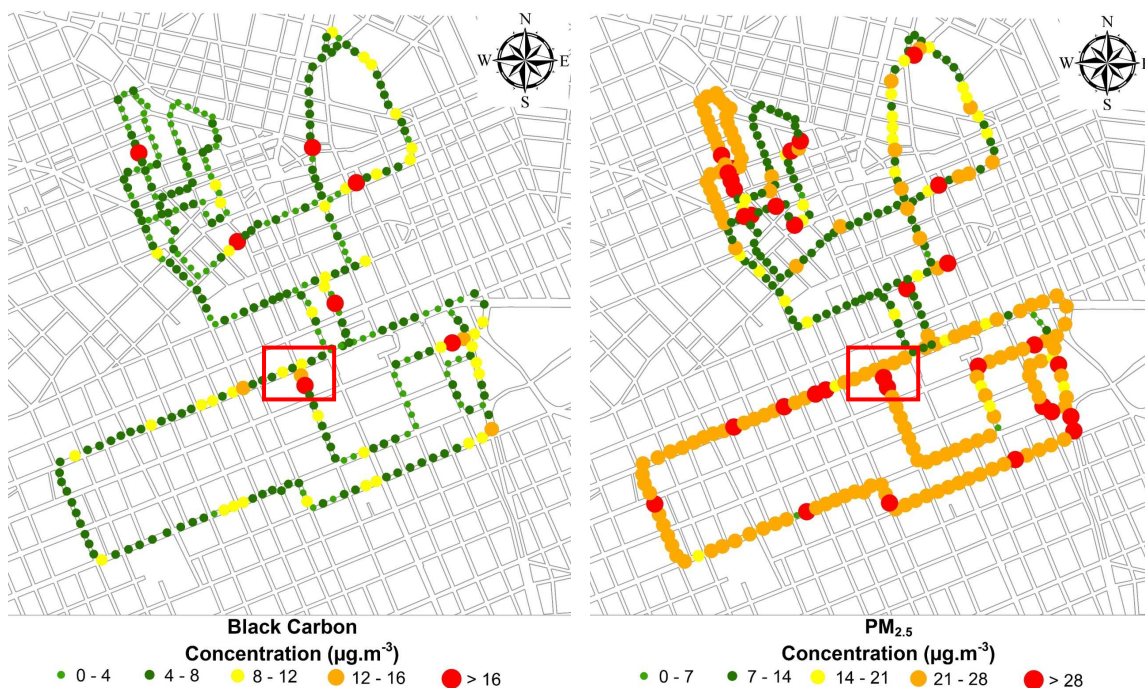


Figure 4.2.9 Spatial distribution of aggregated median BC concentrations (left) and PM_{2.5} (right) using three morning runs.

Measurements of NO/NO₂ concentrations

Comparison with reference monitor and sampling sites

The results obtained from the comparison between the Ogawa samplers and the chemiluminescence monitor are shown in Table 4.2.5. It can be observed concordant values obtained by both methods. Besides, standard deviations of replicate measurements of the six samples taken for this purpose were low, which demonstrates the good repeatability of the method.

Table 4.2.5 Average NO₂ concentration measured by chemiluminescence monitor and Ogawa samplers. The sampling period started on June 27th at the ground level and on June 30th 2016, at 3 m above ground level.

Time	IAP (NO ₂ / µg m ⁻³)	Ogawa (NO ₂ / µg m ⁻³)
1 week – 3 m above ground level	44.68	40.81 ± 2.65
1 week – ground level	34.26	41.00 ± 2.65
2 weeks – 3 m above ground level	29.07	35.35 ± 2.52
2 weeks – ground level	28.13	38.46 ± 1.19

Figures 4.2.10 and 4.2.11 show results of the measurements of nitrogen oxides for samples collected from the 29th of July to the 12th of August and from the 15th to the 29th of August 2016 at all the 11 locations where the Ogawa samplers were installed.

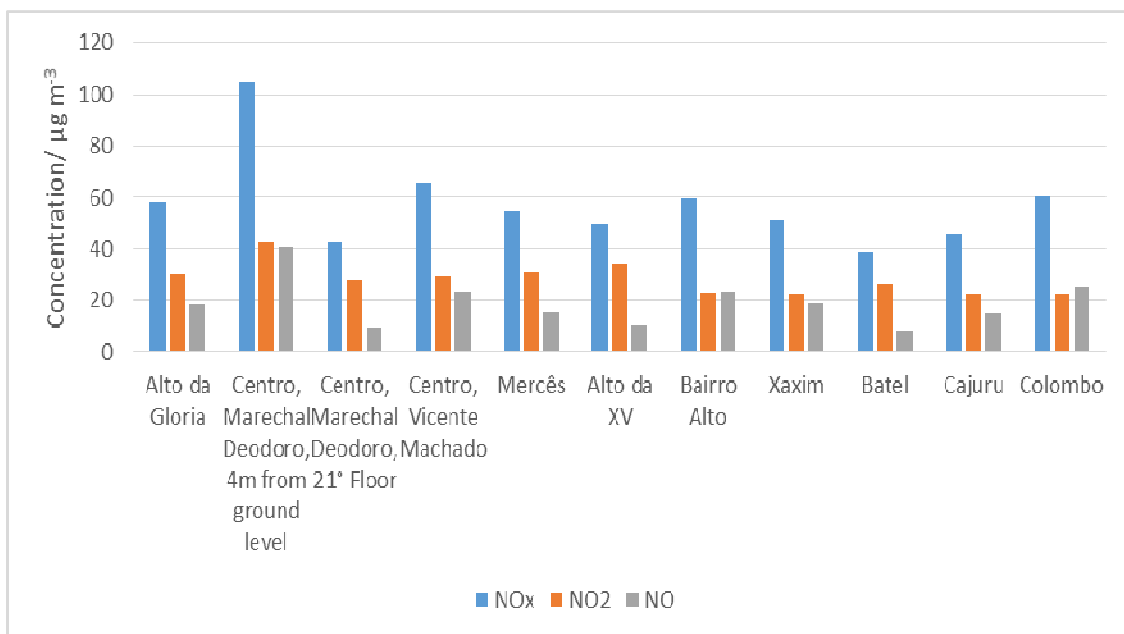


Figure 4.2.10 NO, NO₂ and NO_x concentrations between 29th July and 12th August, 2016.

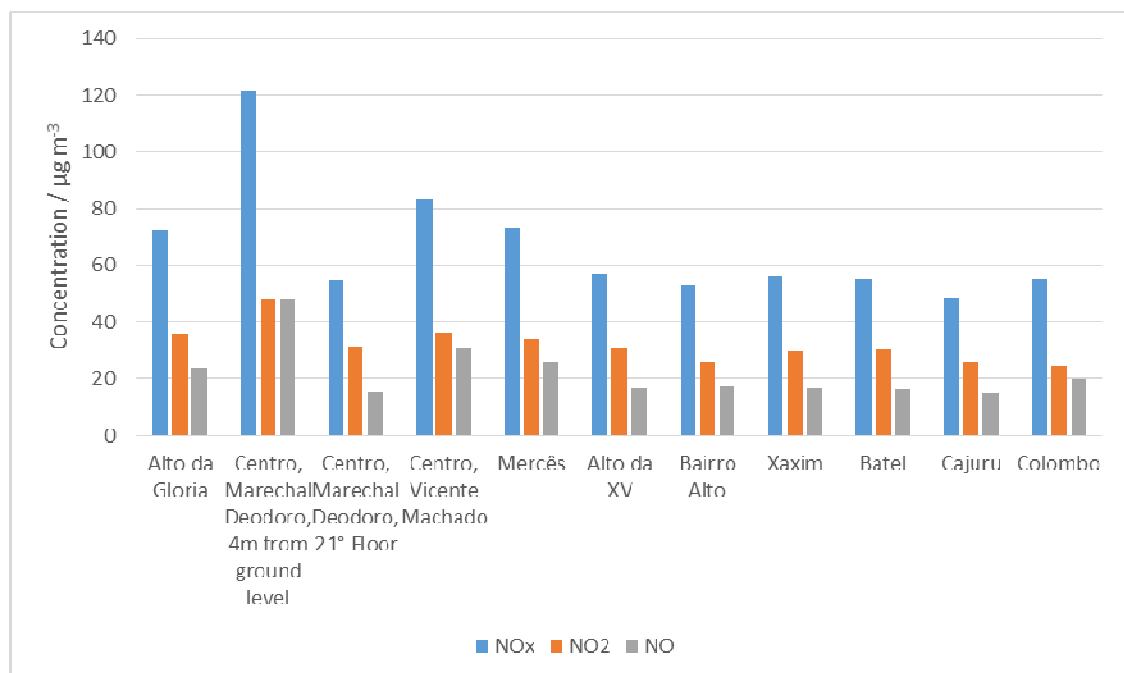
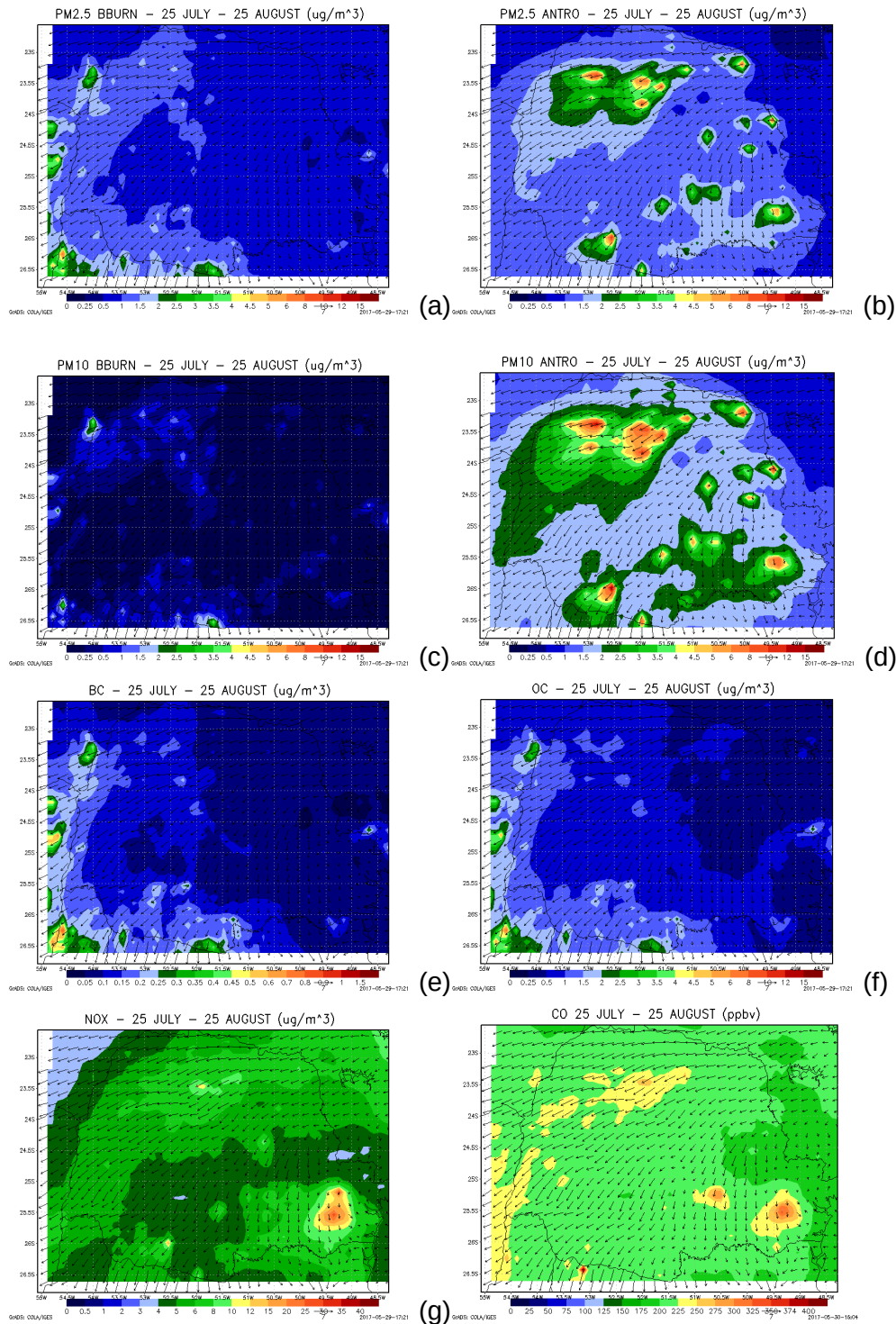


Figure 4.2.11 NO, NO₂ and NO_x concentrations between 15th and 29th August, 2016.

As shown in the Figures 4.2.10-11, the concentration profiles of NO and NO₂ in the second sampling fortnight were similar to the ones recorded in the first fortnight. The highest concentrations were observed at 3 m above ground level of Marechal Deodoro street, which is in the central region of Curitiba with intense vehicular traffic. When compared to the concentrations registered at roof level (corresponding to the 21st floor), it reveals that the concentrations were higher, because the buildings that form the street canyon reduced the ventilation and the dispersion of pollutants at street level.

4.3 Regional modeling of long-range transported PM and BC

Analyzing the regional model average fields for the period from the 25th of July to the 25th of August, 2016, there are some particularities relating the distribution of pollutants (Figure 4.3.1).



4.3.1 For the period 25th July to 25th August average PM_{2.5} from biomass burning (a) and anthropogenic sources [$\mu\text{g}/\text{m}^3$] (b), PM₁₀ from biomass burning (c) and anthropogenic sources [$\mu\text{g}/\text{m}^3$] (d), BC [$\mu\text{g}/\text{m}^3$] (e), OC [$\mu\text{g}/\text{m}^3$] (f), NO_x [ppbv] (g) and CO [ppbv] (h).

The PM emitted by biomass burning ($PM_{2.5}$ and PM_{10}) is concentrated in the western and mid-south region of the state of Paraná. Both BC and OC presented higher values in the same regions, possibly due to the underestimation of the urban emission by the EDGAR-HTAP global database.

The anthropogenic emissions of $PM_{2.5}$, PM_{10} , NO_x and CO presented a similar distribution in the state of Paraná, with high concentrations over the Metropolitan Region of Curitiba and cities of economic importance, such as Londrina, Maringá, Campo Mourão, Ponta Grossa and Cascavel (see Figure 4.3.2).

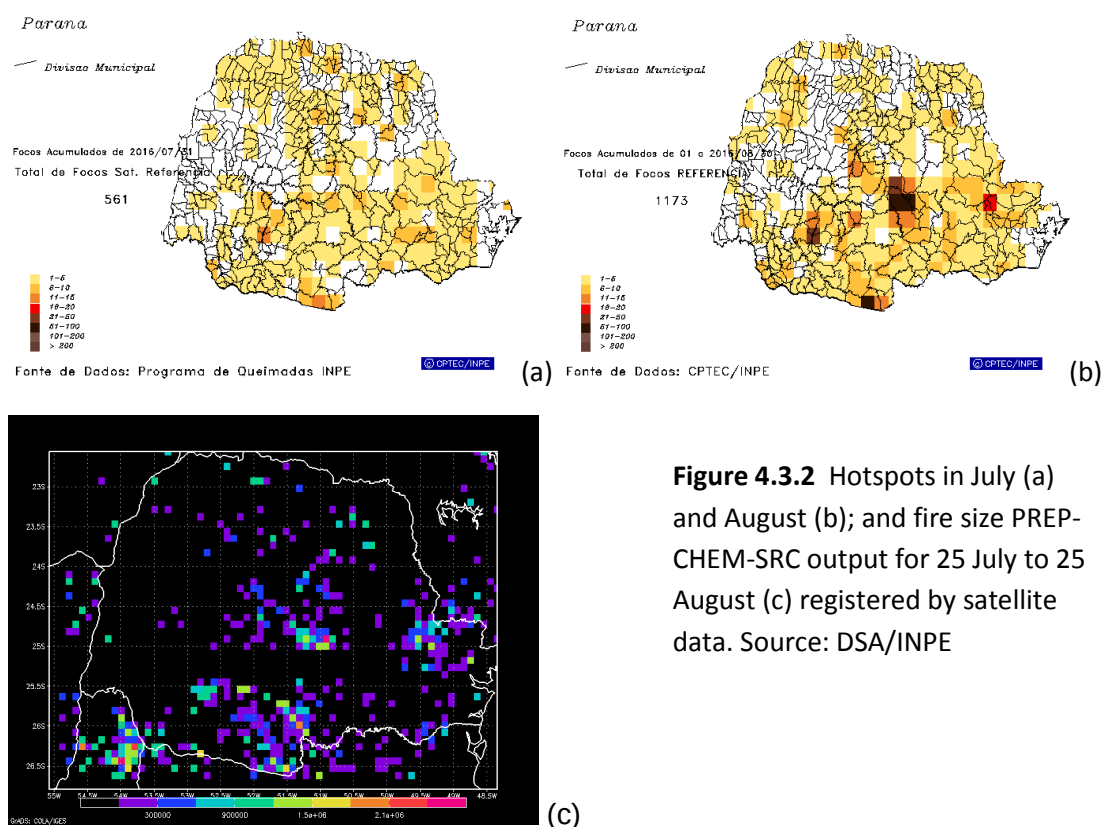


Figure 4.3.2 Hotspots in July (a) and August (b); and fire size PREP-CHEM-SRC output for 25 July to 25 August (c) registered by satellite data. Source: DSA/INPE

Figures 4.3.3, 4.3.4 and 4.3.5 show the averaged impact of the long-range transported pollution from sources outside the Curitiba municipality. For NO_x , Fig. 4.3.3 depicts the strong impact of the industrial sources in Araucária (southwest) and Colombo (north).

A similar pattern is found in terms of long-range $PM_{2.5}$ emitted by anthropogenic sources (Fig. 4.3.4, right part). Biomass burning was concentrated in western and mid-south region of the state of Paraná, with no significant contribution of the fire sources to the urban region during this winter period (see $PM_{2.5}$ impact from biomass burning in Fig. 4.3.4, left part).

The simulated regional contributions of BC and OC (Fig. 4.3.5) were low, since a local and more detailed inventory of the Paraná industrial emission of BC and OC was missing (model output based on existing CCATT-BRAMS coarse emission inventories only). The long-range contributions to Curitiba's BC and OC levels should thus be considered as poorly represented in model results and most likely under-estimated.

Figure 4.3.3 Simulated NO_x levels over the eastern part of the Paraná state for the period 20th July – 28th August, using IAP emission inventory. Emissions within the Curitiba municipality are excluded. Curitiba city center marked with white circle. Unit: $\mu\text{g}/\text{m}^3$.

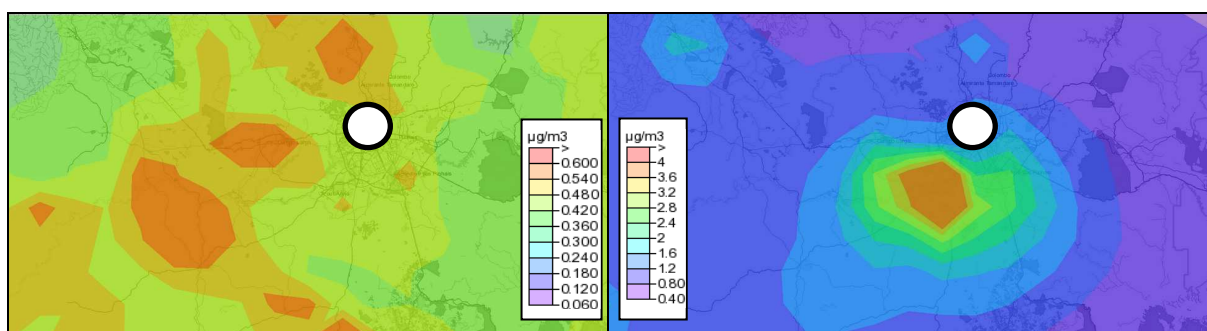
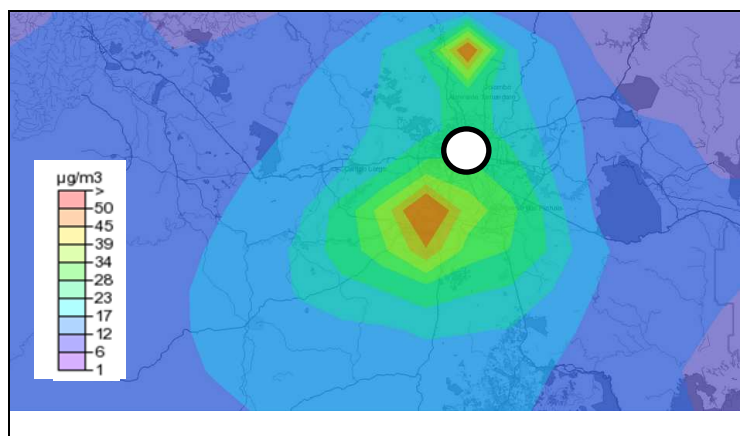


Figure 4.3.4 Simulated average $\text{PM}_{2.5}$ contribution from 20th July to 28th August 2016 from biomass burning (left) and anthropogenic emissions (IAP inventory excluding sources within the Curitiba municipality, right). Curitiba city center marked with a white circle.

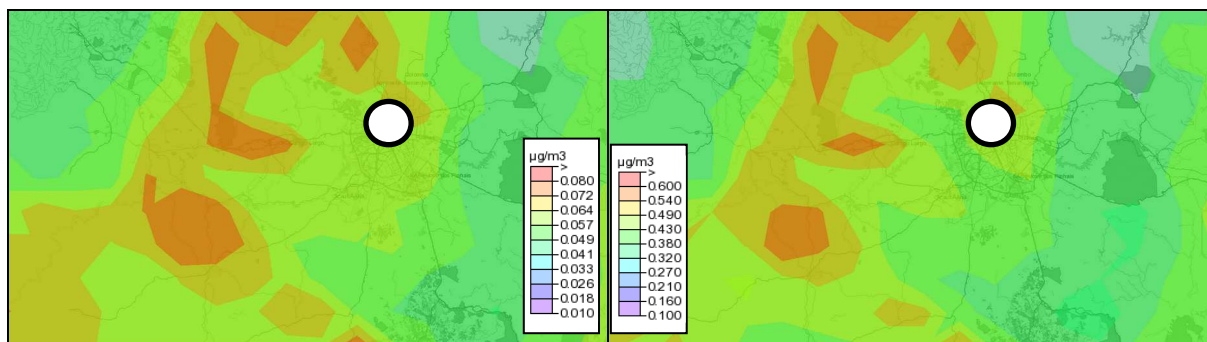


Figure 4.3.5 Simulated concentrations of BC (left) and OC (right) during 20th July – 28th August 2016 from the summed contributions of anthropogenic (EDGAR) and biomass burning (3BEM). Curitiba city center marked with a white circle.

4.4 Local dispersion modeling and integrated analysis

Simulated NO_x , BC and $\text{PM}_{2.5}$ levels in the Marechal Deodoro street canyon

The measurements conducted at the Marechal Deodoro site provided a good understanding of how local traffic emissions contribute to increased pollution levels inside the street canyon (see Fig. 4.4.1).

Figure 4.4.1 Monitored mean concentrations at Marechal Deodoro roof level and street level during the monitoring campaign 25th July – 25th August 2016. Unit: $\mu\text{g}/\text{m}^3$.

Note: Photo shows another street in Curitiba, used just for illustrating a typical street canyon.



Following the method outlined in Section 3.1, we will first evaluate the emissions from the public (buses) and private transport, by comparing model output with measurements in a street canyon. The best available data we have for this task are the BC hourly data from the Marechal Deodoro station, with one monitor situated at the roof and the other down in the street canyon, close to the road. We also have NO_x data from passive samplers located at both roof and street levels, two two-week average values for each location. Since emission factors for NO_x are fairly well known and likely more reliable than emission factors for BC, we start with NO_x modelling, followed by model simulations of BC and finally $\text{PM}_{2.5}$.

The traffic volumes obtained from the speed trap/radar data collected at Marechal Deodoro during the monitor campaign indicated a weekly average of 19700 veh/day, with a workday average of 22500 veh/day (see Fig. 4.4.2). Traffic count data during morning and afternoon peak hours of 2012 reported 25-35% higher volumes. After discussing these data with IPPUC, it was decided – based on micro-modeling of the area - to raise the vehicle volumes of private traffic to 24075 veh/day (average for the whole week). A fleet composition of 93% cars, 5% utility (light diesel vehicles) and 2% trucks (heavy diesel vehicles) was assumed. The temporal variation was taken directly

from the hourly measured speed trap/radar data, in order to catch minor variations from day to day.

On average, the volume of buses passing the monitoring station at Marechal Deodoro was 469 veh/day, thus accounting for a small fraction of the total traffic flow on the street. Their temporal variation was taken from the bus time tables.

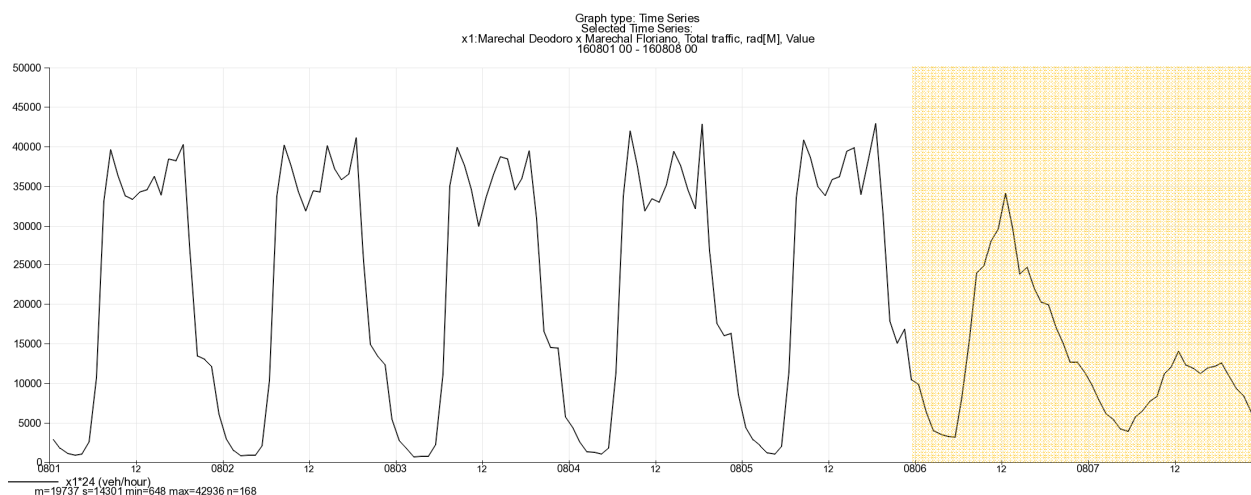


Fig. 4.4.2 Hourly traffic volume along Marechal Deodoro during one of the weeks of the monitoring, as registered by the speed trap/radar located on Marechal Deodoro street, close to the monitoring station. Weekend days marked in pink.

NO_x levels were measured with passive samplers located at the Marechal Deodoro roof, as well as at the street level. The street canyon model was run also for NO_x (Table 4.4.1). The measured increment in NO_x levels (62/66 $\mu\text{g}/\text{m}^3$) from the roof (urban background) level down into the street canyon is very similar to the simulated contributions from buses and private cars, summed together (75/69 $\mu\text{g}/\text{m}^3$). Since we expect NO_x emission factors to be representative, this indicates that traffic volumes should be fairly well estimated.

Running the OSPM model, with traffic intensity determined separately (see Section 3.3) for buses and for private vehicles, we get results according to Fig. 4.4.3 and Table 4.4.1.

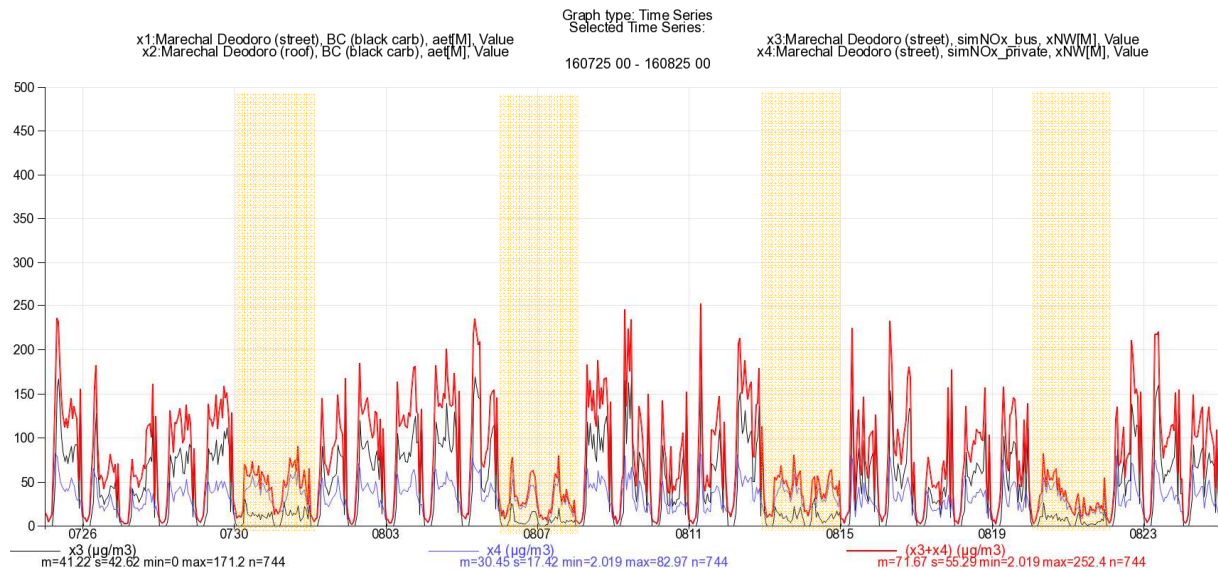


Fig. 4.4.3 Simulated NO_x levels at Marechal Deodoro: buses (black), private vehicles (blue) and the sum of both (red).

Table 4.4.1 Monitored and simulated NO_x levels at Marechal Deodoro. Note that the simulation for the second period ended a few days earlier (Aug 25) as compared to the monitored values.

	monitored NO _x (µg/m ³)			simulated NO _x - street (µg/m ³)		
<i>Period</i>	<i>street</i>	<i>roof</i>	<i>increment</i>	<i>public transport</i>	<i>private traffic</i>	<i>summed</i>
Jul 29 – Aug 12	105	43	62	43	32	75
Aug 15 – Aug 29	122	55	66	40	29	69

Performing the same street canyon modeling for private traffic and buses, but for BC instead of NO_x, the summed output concentrations show up as the red line in Figure 4.4.4, considerably lower than the monitored levels (black line in Figure 4.4.4). Referring to the rather good similarity between simulated and monitored NO_x levels, we conclude that the emission factors used for BC are strongly underestimated. However, there may also be differences between simulated and monitored levels due to other factors. A detailed visual inspection of the measured BC contribution reveals one event where measured levels show up in a different and non-expected way. While monitored levels in general are reduced during the weekends, there is a long event with high BC levels during the third weekend (August 13-14), with high levels also during nighttime. This event is most likely generated by non-traffic sources and is not expected to be explained by our street canyon model.

Still it is clear that vehicle emission factors are strongly underestimating the BC emissions. Figure 4.4.4 reveals that simulated BC levels are too low, but there seems to be a temporal variation close to the measured one. A multiple regression (EXCEL), forcing the model to pass the origin (i.e. the regression constant or bias set to zero) yielded two slope coefficients, for the independent variables “impact bus traffic” a coefficient of 1.2 and for the “impact private traffic” 5.0. Note that the weekend August

13-14 was excluded in the regressed time series, since it apparently was not caused by traffic impact. Thus, the regression model suggests a smaller 20% increase of the bus impact signal, but scaling up the private traffic impact as much as 5 times. With the regressed relations, the simulated BC levels follow closely the measured variations (Fig. 4.4.5) and average levels (Table 4.4.2).

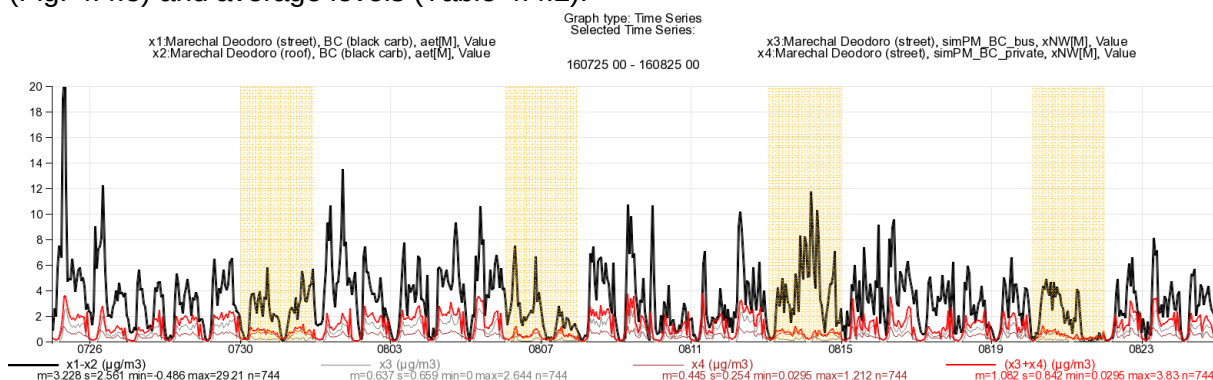


Fig. 4.4.4 Hourly data of locally generated black carbon (BC) from measurements (street minus roof concentrations, in black), simulated impact from buses (thin grey), from private vehicles (thin brown) and total simulated contribution from the street (red). Unit: $\mu\text{g}/\text{m}^3$. Weekends are indicated in yellow.

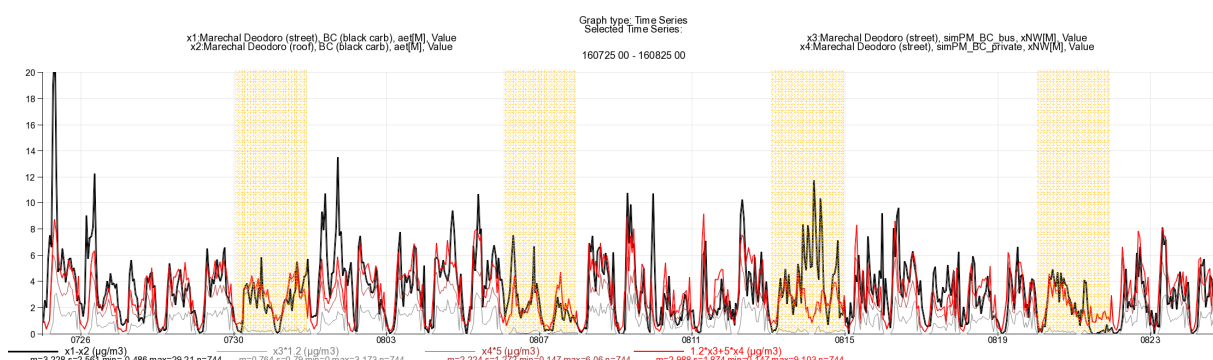


Fig. 4.4.5 Hourly data of locally generated black carbon (BC) from measurements (street minus roof concentrations, in black), and simulated – after multiple regression - impact from buses (thin grey), from private vehicles (thin brown) and total simulated contribution from the street (red). Unit: $\mu\text{g}/\text{m}^3$. Weekends are indicated in yellow. The correction factors were 1.2 for buses and 5.0 for private traffic.

Table 4.4.2 Monitored and simulated BC levels at Marechal Deodoro.

Unit: $\mu\text{g}/\text{m}^3$	monitored BC			simulated BC (street)		
	street	roof	increment	public transport	private traffic	summed
Emission factors from literature (Fig. 4.4.3)	5.52	2.29	3.23	0.64	0.45	1.08
Correction based on multiple regression (Fig. 4.4.4)	5.52	2.29	3.23	0.76	2.22	3.00

From the left diagram in Fig 4.4.6 we can follow the daily variations in the measured BC contributions from the traffic, being almost zero at night and following the traffic variations during the day. The simulated impact, after the multiple regression correction, follows well the measured daily variation during weekdays. However, if the same comparison is made for the weekend 13th-14th August, 2016, there is a strong peak in measured BC during the night and morning hours that is not explained by the simulated traffic. Apparently there was an unidentified source of black carbon emitting large amounts of BC during this particular weekend. Since a high peak was observed that weekend also at roof level, it is possible that the origin is distant and that the difference between street and roof levels as displayed in the right part of Figure 4.4.6 is an artefact of how the two instruments registers these very increased levels. In other word, it is not necessary that the source behind the weekend event is located in the city center.

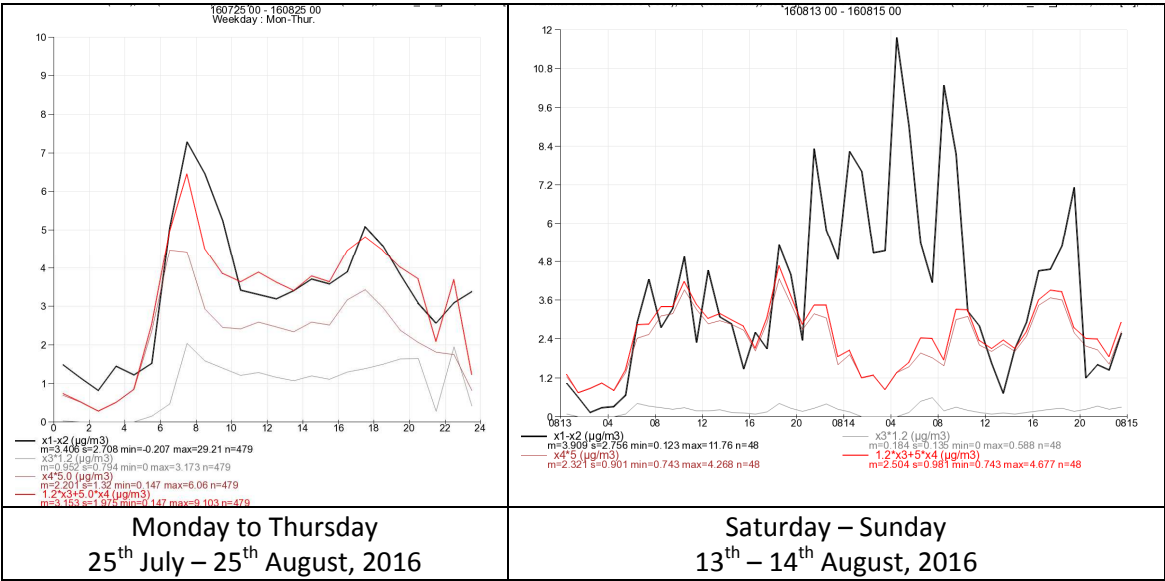


Fig. 4.4.6 Daily variation during workdays Monday to Thursday (left) and during the weekend 13th – 14th August, 2016 with measured BC levels (black) and simulated bus impact (grey), private traffic impact (brown) and summed traffic impact (red).

The simulated impact of PM_{2.5} emissions generated by the traffic inside the street canyon is presented in Fig. 4.4.7. There is no hourly data to compare with, but for average levels we can use the measured PM_{2.5} average value at roof level (7.3) and the indirectly determined PM_{2.5} level on the street (3 times the BC level, 16.6 µg/m³). Table 4.4.3 summarizes the comparison.

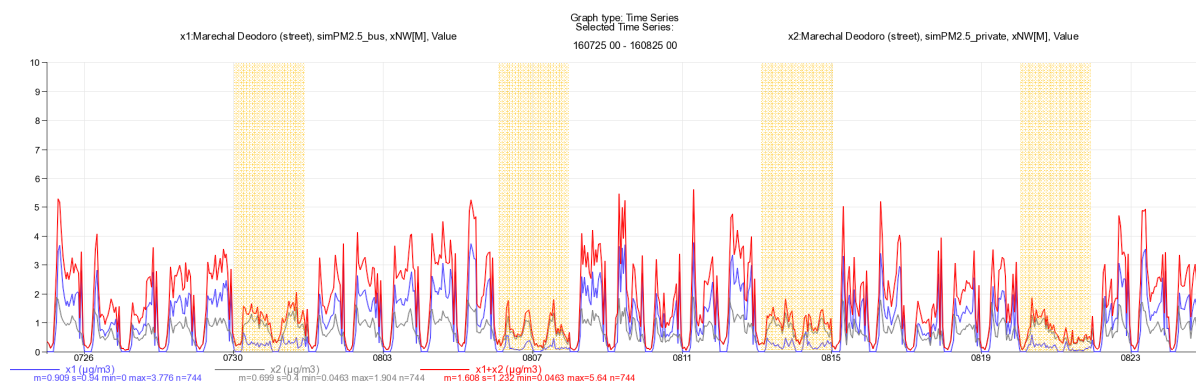


Fig. 4.4.7 Hourly simulated data of locally generated PM_{2.5} impact from buses (grey), private vehicles (blue) and summed traffic contribution (red). Units: µg/m³.

Table 4.4.3 Monitored and simulated PM_{2.5} levels at Marechal Deodoro.

Unit: µg/m ³	monitored BC			simulated BC (street)		
	<i>street</i>	<i>roof</i>	<i>increment</i>	<i>public transport</i>	<i>private traffic</i>	<i>summed</i>
Emission factors from literature (Fig. 4.4.3)	16.6 ¹	7.3	9.3	0.91	0.70	1.61

¹ indirectly determined as 3 times the monitored BC levels

Comparing the simulated total PM_{2.5} (1.6 µg/m³) with the monitored increment (9.3 µg/m³), there is a factor of 5-6 difference. The simulated PM_{2.5} is only based on combustion exhausts from the vehicles, so we would expect necessary to add also a non-exhaust part resulting from road/tyre/brake wear and road dust resuspension due to the turbulence created within the street canyon. However, a rule of thumb for cities not using studded tyres in the winter (as in Sweden) is that such non-exhaust fraction for PM_{2.5} may equal some 50% of the total, not 5-6 times more. Thus it is likely and logical that the exhaust PM_{2.5} emission factors are, like the BC factors, also strongly underestimated. For simplicity we will avoid to separate exhaust and non-exhaust contributions, and instead conclude that the traffic impact to PM_{2.5} levels should be increased with a factor of 5, in order to be consistent with monitored PM_{2.5} levels in Marechal Deodoro.

Monitored and simulated NO_x, BC and PM_{2.5} levels in the urban background

The campaign using passive NO_x samplers was motivated to complement the pointwise IAP NO₂/NO_x data to obtain the spatial distribution of this pollutant, but also to generate data for evaluating model results. The results for the two two-week long measurements have been presented in Section 4.2. Here we compared monitored and simulated concentration levels for each period, but the results are presented as an average for both periods.

The simulated NO_x are summed up with a long-range transport (LRT) contribution from the regional model based on the IAP inventory, excluding emissions within the Curitiba municipality, plus the different local model results (Table 4.4.4, Fig. 4.4.8). Since the

industrial emissions in Auracária, as estimated in the IAP inventory, were included in the regional model results, the local simulation was made with only the IAP emissions located inside the Curitiba municipality and the small industrial emissions of the SMMA inventory.

Table 4.4.4 Comparison between simulated contributions and monitored NO_x levels for the period 29th July to 29th August, 2016. Unit: µg/m³. Contributions marked in red, total NO_x levels in black.

	LRT	large industries within the municipality (IAP inventory)	small industries (SMMA)	public transport	private traffic	simulated total	monitored
Mar. Deodoro	31.9	0.1	0.5	8.7	13.6	54.8	45.8
Vic. Machado	32.2	0.1	0.7	9.3	14.4	56.7	62.0
Merces	31.9	0.2	0.7	9.7	13.9	56.3	67.7
Xaxim	37.7	0.1	0.1	5.2	11.8	54.9	52.6
Vila Petropolis	26.4	0.1	0.1	1.8	6.7	35.0	59.3
Alto da Gloria	31.9	0.1	0.4	7.4	13.5	53.2	61.9
Alto da Rua XV	31.2	0.1	0.3	5.5	12.6	49.7	51.5
Bairro Alto	29.0	0.1	0.1	3.1	6.6	38.9	53.3
Batel	32.9	0.2	0.9	8.3	15.3	57.5	42.6
Cajuru	31.0	0.1	0.1	4.8	9.0	45.0	46.2
IAP_CIC	44.9	0.2	1.4	6.7	24.4	77.6	66.8
IAP_PAR	32.9	0.1	0.7	10.9	14.6	59.1	41.3
IAP_STC	27.0	0.1	0.1	2.5	4.8	34.6	28.0

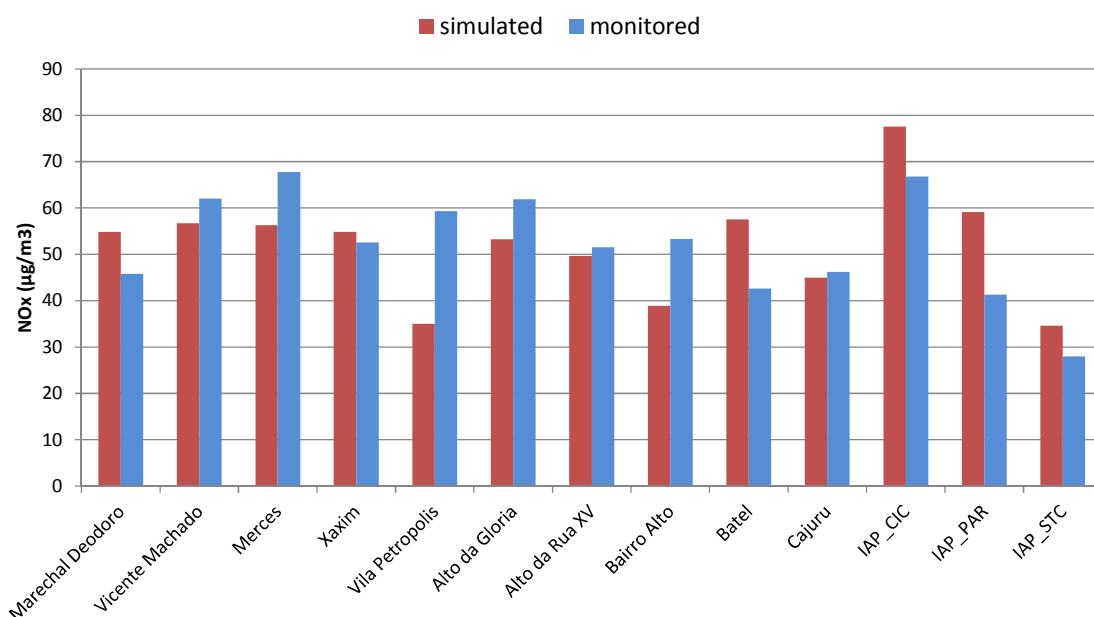


Figure 4.4.8 Comparison between simulated NO_x urban background levels (red) and monitor data (blue) for the period July 29th to August 29th 2016. The IAP data are taken from the IAP monitoring network, the others measured with passive samplers.

The overall result, as illustrated in Fig. 4.4.8, is fairly good in terms of average concentration levels, simulated data has an average of 51.8 µg/m³ and the measured 52.2 µg/m³. However, the spatial correlation is 0.43, i.e. there are larger differences between simulated and observed NO_x concentrations at individual stations. The main contributions come from the outside (LRT) and the mobile sources. Since there is a

lack of local emissions in the inventory, e.g. domestic sources, off-road working vehicles, heating, cooking, it is likely that the simulated impact is somewhat overestimated. A smaller overestimation of the simulated local traffic impact was found in the street canyon comparison. For the regional impact, it is likely that the coarse spatial resolution of the model (approximately 9x9 km²) will lead to an overestimated impact of the industrial IAP emissions just outside the municipality (a lower impact was obtained by the local Gaussian model, not shown in this report). However, the emission sources lacking in the inventory are not expected to yield high NO_x contributions, so the general picture of Table 4.4.4 should be correct.

After adjusting the traffic emission factors for **BC**, we will now compare the city-wide simulations that show the spatial distribution of the air pollution levels, including contributions from both LRT pollution and the impact of local sources. The comparison of hourly data is made at the Marechal Deodoro roof level station (Fig. 4.4.9) and the residential station Sitio Cercado (Fig. 4.4.10). The comparison of mean monitored and simulated BC levels are presented in Tables 4.4.5 and 4.4.6.

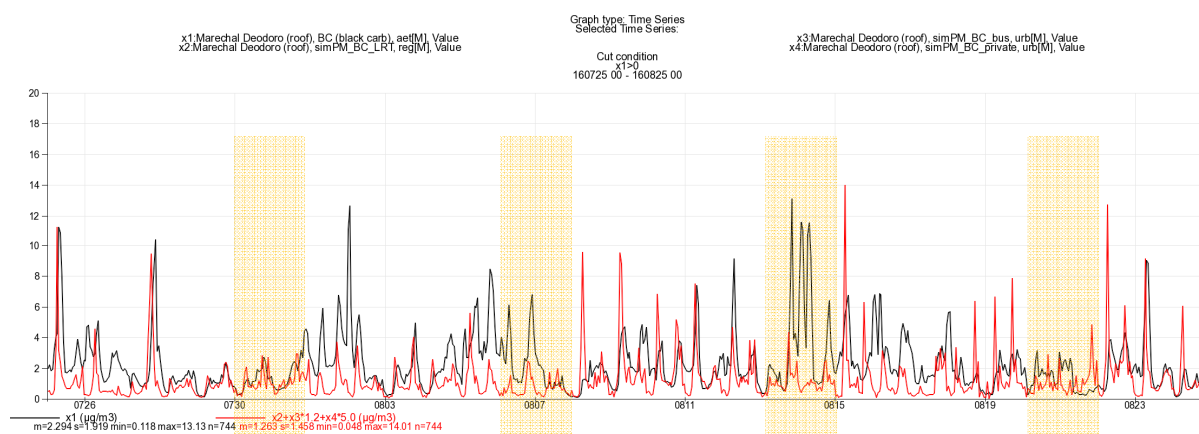


Fig. 4.4.9 Monitored and simulated BC levels at Marechal Deodoro roof level: Monitored (black), simulated (red) consisting of regional model contribution plus local impact of buses and private vehicles. The local contribution has been modified according to the regression results from the street canyon Marechal Deodoro.

Table 4.4.5 Monitored and simulated contributions to BC levels at Marechal Deodoro roof level.

	Contribution (µg/m ³)	comment
Long-range transport (LRT)	0.06	<i>This contribution is likely underestimated due to lack of regional emission inventories for BC</i>
Public transport (buses)	0.13	
Private traffic	1.07	
Summed:	1.27	
Monitored:	2.29	
Unknown sources:	1.02	<i>Except for the underestimated LRT, there may also be a contribution from residential combustion within the city (not included in the model simulation).</i>

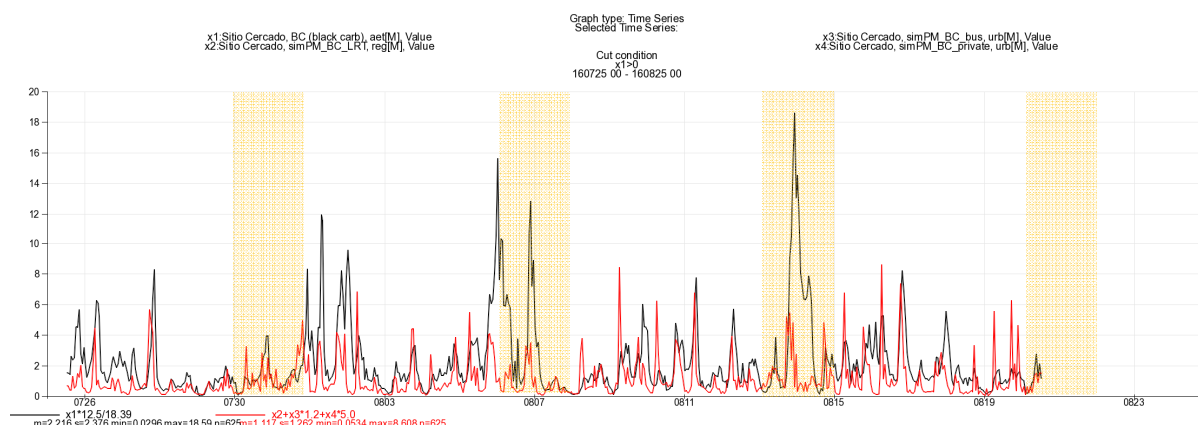


Fig. 4.4.10 Monitored and simulated BC levels at Sitio Cercado: Monitored (black), simulated (red) consisting of regional model contribution plus local impact of buses and private vehicles. The local contribution has been modified according to the regression results from the street canyon Marechal Deodoro.

Table 4.4.6 Monitored and simulated contributions to BC levels at Sitio Cercado

	Contribution ($\mu\text{g}/\text{m}^3$)	comment
Long-range transport (LRT)	0.07	<i>This contribution is likely underestimated due to lack of regional emission inventories for BC</i>
Public transport (buses)	0.07	
Private traffic	0.98	
Summed:	1.11	
Monitored:	2.22	
Unknown sources:	1.11	<i>Except for the underestimated LRT, there may also be a contribution from residential combustion within the city (not included in the model simulation).</i>

At both stations the simulated mean BC levels are only half of monitored, which indicate that there are unknown sources contributing. It seems quite clear that part of this can be explained by an underestimated long range contribution. The regional emission inventory does not include any detailed BC emissions from anthropogenic sources, e.g. the Araucária industrial zone. There are clearly large-scale events, e.g. 1-2 August and 14th August where the measured impact is simultaneously high in both stations (Fig. 4.4.11). The high peaks at Sitio Cercado can also be partly explained by residential combustion in the neighborhood. The ParCur staff operating the monitor station at Sitio Cercado reported events with smell of wood combustion.

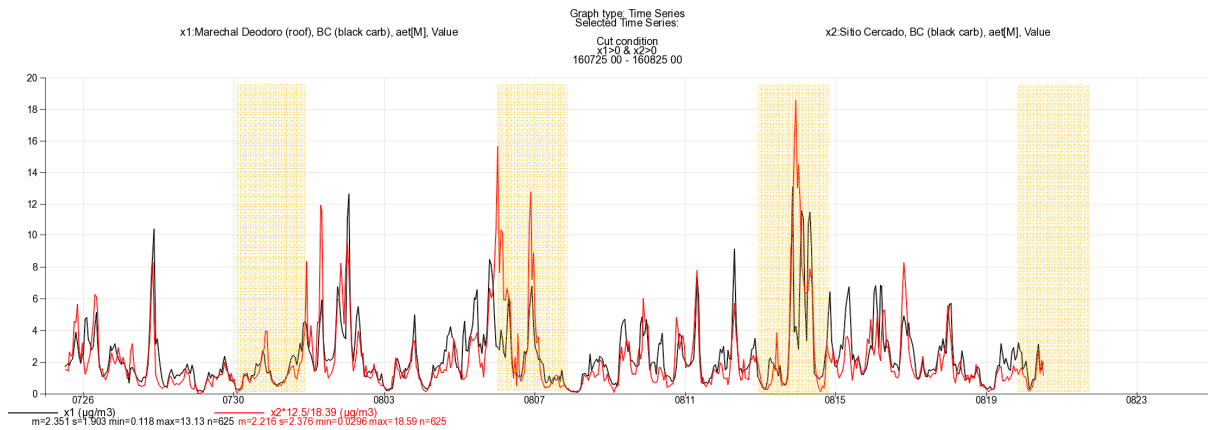


Fig. 4.4.11 Monitored and simulated BC levels at Marechal Cercado roof level (black) and Sitio Cercado (red).

In summary, the comparison of BC levels at the two stations indicates rather uniform urban background levels of about $2 \mu\text{g}/\text{m}^3$ over the city. About half comes from local traffic, the other half from long-range transport and unknown local sources, likely associated with residential combustion. A similar level of BC around $2 \mu\text{g}/\text{m}^3$ was found in the historical data set from UFPR campus (Fig. 4.2.3), also supporting a rather homogenous spatial distribution of this pollutant.

The comparison of $\text{PM}_{2.5}$ is presented in Fig. 4.4.12/Table 4.4.7 (Marechal Deodoro roof level) and Fig. 4.4.13/Table 4.4.8 (Sitio Cercado). While measured and simulated $\text{PM}_{2.5}$ levels are fairly similar in the city center, the monitored levels in the residential area Sitio Cercado are various times higher than simulated and also much higher than in the city center. Local sources are thus likely to dominate the $\text{PM}_{2.5}$ impact in this area. The historical $\text{PM}_{2.5}$ data set from the UFPR campus (Fig. 4.2.3), with mean levels of $10 \mu\text{g}/\text{m}^3$, is more similar to the levels at Marechal Deodoro roof level and much lower than those registered at the residential site Sitio Cercado.



Fig. 4.4.12 Monitored and simulated daily $\text{PM}_{2.5}$ levels at Marechal Deodoro roof level: Monitored (black), simulated (red) consisting of regional model contributions from anthropogenic and biomass burning plus local impact of buses, private vehicles and industry within the Curitiba municipality. The local contribution was modified according to the results obtained from the street canyon Marechal Deodoro.

Table 4.4.7 Monitored and simulated contributions to PM_{2.5} levels at Marechal Deodoro roof level.

	Contribution (µg/m ³)	comment
Long-range transport (LRT) from regional model:		<i>Assumed PM_{2.5}/PM₁₀ ratio 0.7 for IAP industrial emissions. LRT includes IAP emissions outside the Curitiba municipality.</i>
- anthropogenic	1.8	
- biomass burning	0.5	
Public transport (buses)	0.8	
Private traffic	1.6	
Industry inside Curitiba municipality	0.6	
Summed:	5.2	
Monitored:	7.3	
Unknown sources:	2.1	

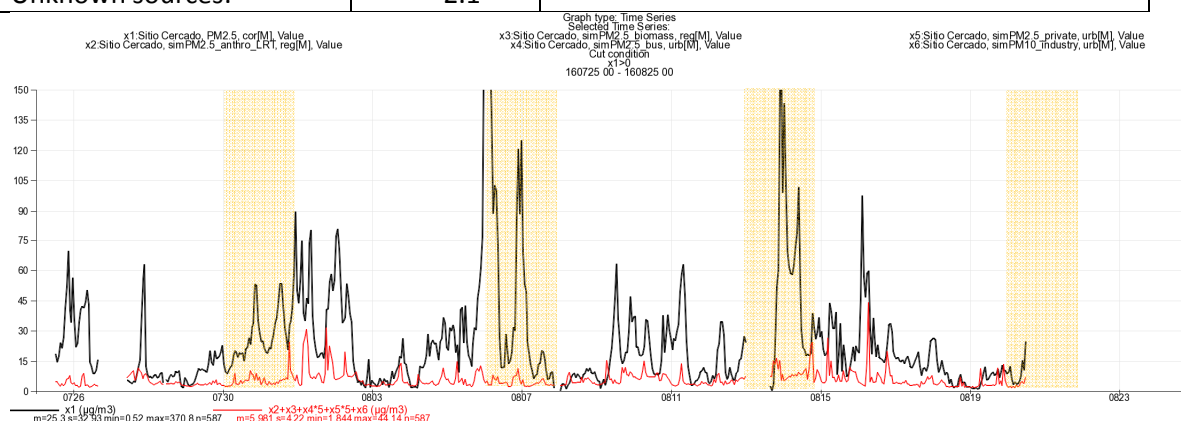


Fig. 4.4.13 Monitored and simulated daily PM_{2.5} levels at the residential station Sitio Cercado: monitored (black), simulated (red) consisting of regional model contributions from anthropogenic and biomass burning plus local impact of buses, private vehicles and industry within the Curitiba municipality. The local contribution has been modified according to the results obtained from the street canyon Marechal Deodoro.

Table 4.4.8 Monitored and simulated contributions to PM_{2.5} levels at the residential station Sitio Cercado.

	Contribution (µg/m ³)	comment
Long-range transport (LRT) from regional model:		<i>Assumed PM_{2.5}/PM₁₀ ratio 0.7 for IAP industrial emissions. LRT includes IAP emissions outside the Curitiba municipality.</i>
- anthropogenic	3.4	
- biomass burning	0.5	
Public transport (buses)	0.4	
Private traffic	1.4	
Industry inside Curitiba municipality	0.6	
Summed:	6.3	
Monitored:	25.3	
Unknown sources:	19.0	<i>Many unidentified sources to PM_{2.5} in this area</i>

Spatial distribution of NO_x, PM_{2.5} and BC contributions from local sources in Curitiba

This section presents the mapped impact of the following local sources, as determined through the integrated analysis of measured and simulated concentrations:

- Public transport (buses)
- Private traffic
- Local industries (smaller, supervised by SMMA, together with larger sources inside Curitiba municipality, supervised by IAP)
- Summed local impact (three earlier contributions together)
- Total impact also including long range transport

Estimated emissions are given for the three local contributions:

- Public transport (buses)
- Private traffic
- Local industries (smaller, supervised by SMMA, together with larger sources inside Curitiba municipality, supervised by IAP)

The maps show the simulated impact for the period 25th July – 25th August 2016.

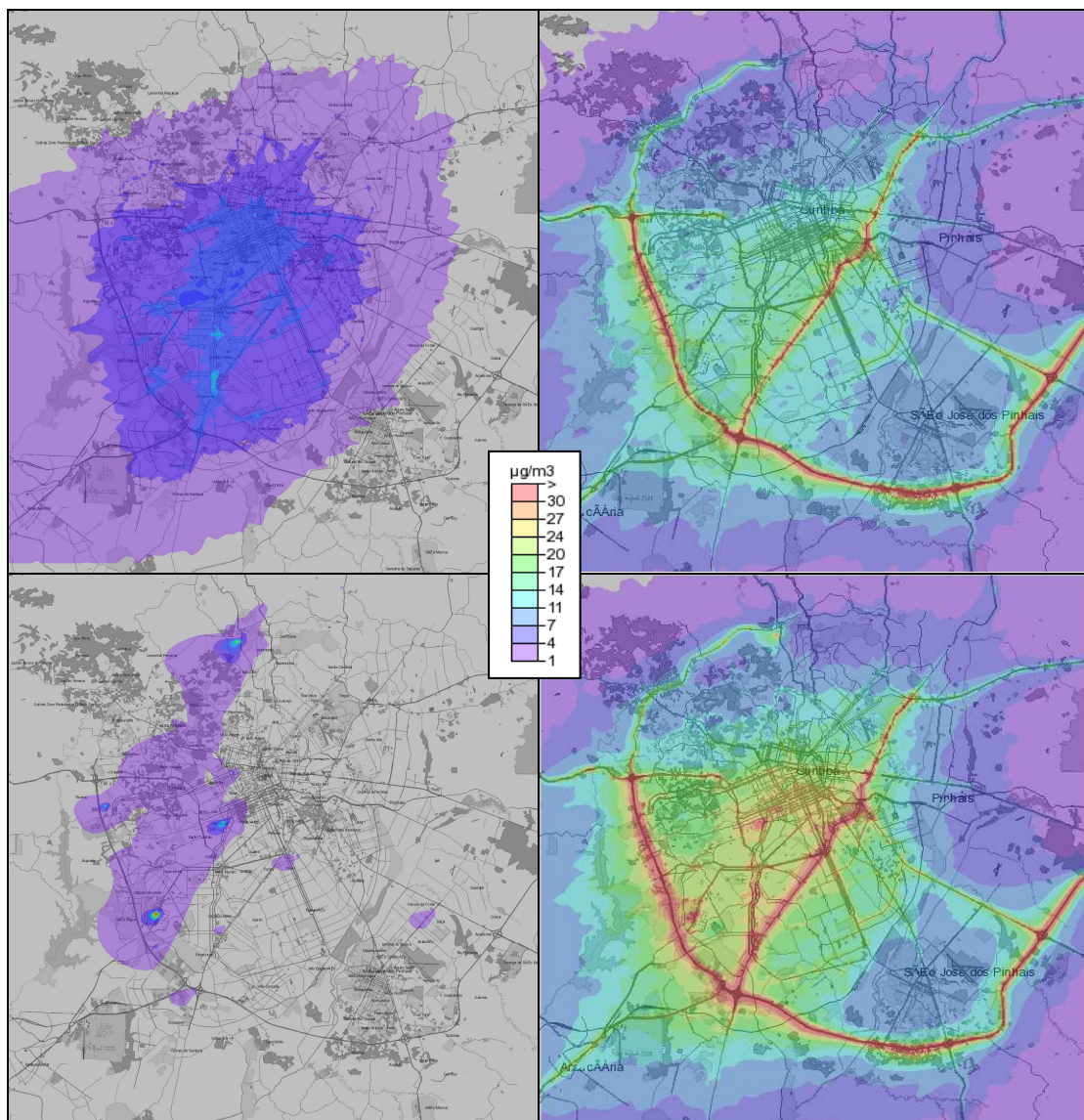


Figure 4.4.14 Simulated average NO_x contribution 25th July – 24th August 2016 from public transport (upper left), private traffic (upper right), local industries (bottom left) and summed local impact.

The local contributions to **NO_x** (Fig. 4.4.14) over the Curitiba city are mainly coming from the traffic. Private traffic dominates over public transport, contributing to 3-4 times higher impact of NO_x. In smaller areas around the industrial sources, there is a dominating impact from those industrial emissions.

Local NO_x emissions contributing to simulated concentration levels as in Fig. 4.4.14, are sector distributed as:

- Public transport (buses): 1 081 tons/year
- Private traffic: 4 686 tons/year
- Industrial (SMMA): 160 tons/year
- Industrial (IAP, inside Curitiba): 107 tons/year

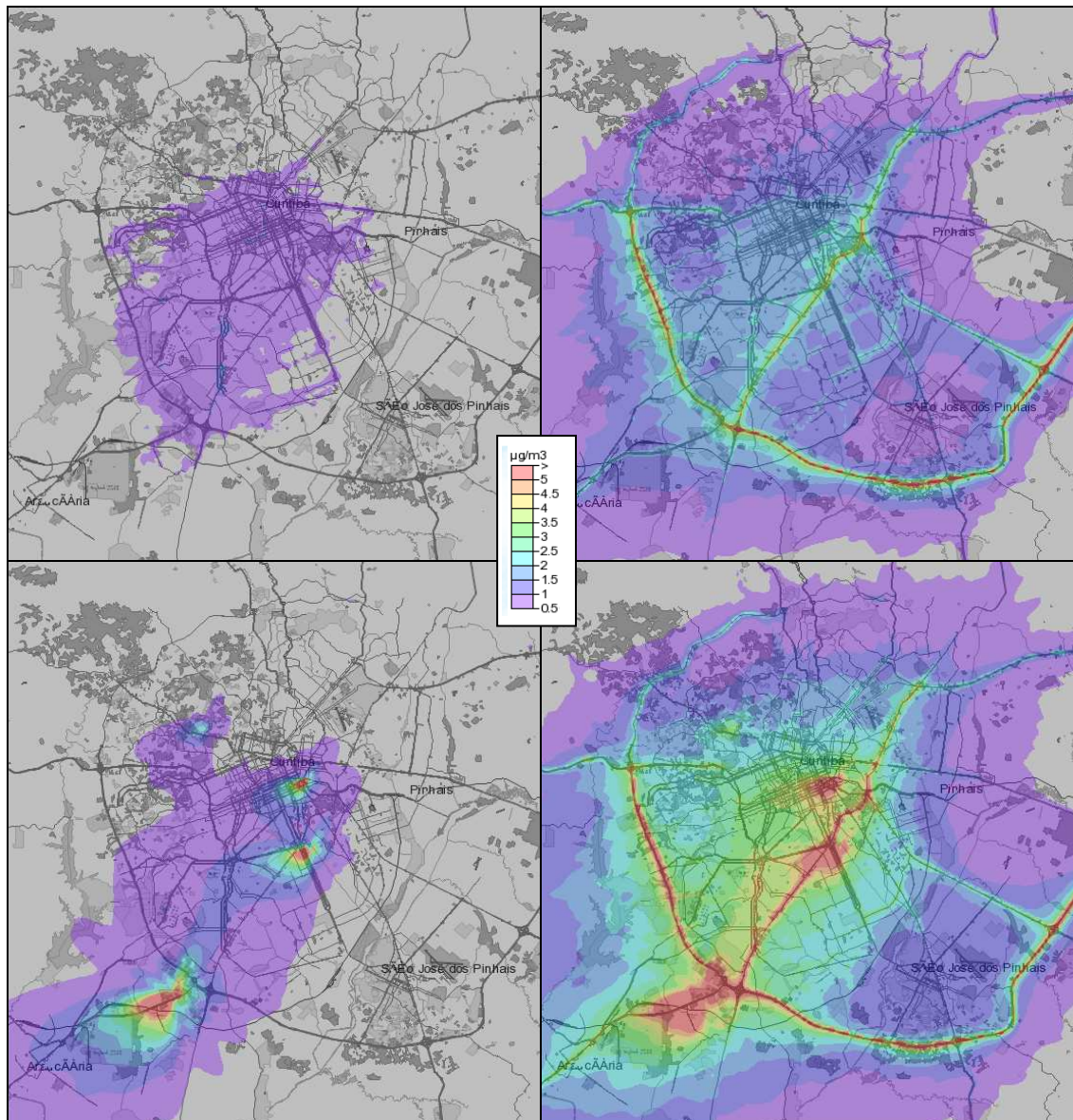


Figure 4.4.15 Simulated average $PM_{2.5}$ contribution 25th July – 24th August 2016 from public transport (upper left), private traffic (upper right), local industries ($PM_{2.5}$ emissions assumed 70% of PM_{10} emissions, bottom left) and summed local impact (bottom right).

Spatial distribution of **$PM_{2.5}$** impact from sources included in the emission inventory is illustrated in Fig. 4.4.15. The PM emissions from industries are reported as PM_{10} , we have assumed $PM_{2.5}$ emissions to constitute 70% of PM_{10} emissions, based on Erlich et al. (2007) which indicate a range of 55%-100% for the ratio $PM_{2.5}/PM_{10}$ in industrial emissions. Buses and private traffic emissions corrected with a factor 5 (the separation highly uncertain since a regression analysis could not be performed for $PM_{2.5}$). Local $PM_{2.5}$ emissions contributing to simulated concentrations as in Fig. 4.4.15, are sector distributed as:

- Public transport (buses): 105 tons/year
- Private traffic: 538 tons/year
- Industrial (SMMA): 329 tons/year
- Industrial (IAP, inside Curitiba): 64 tons/year

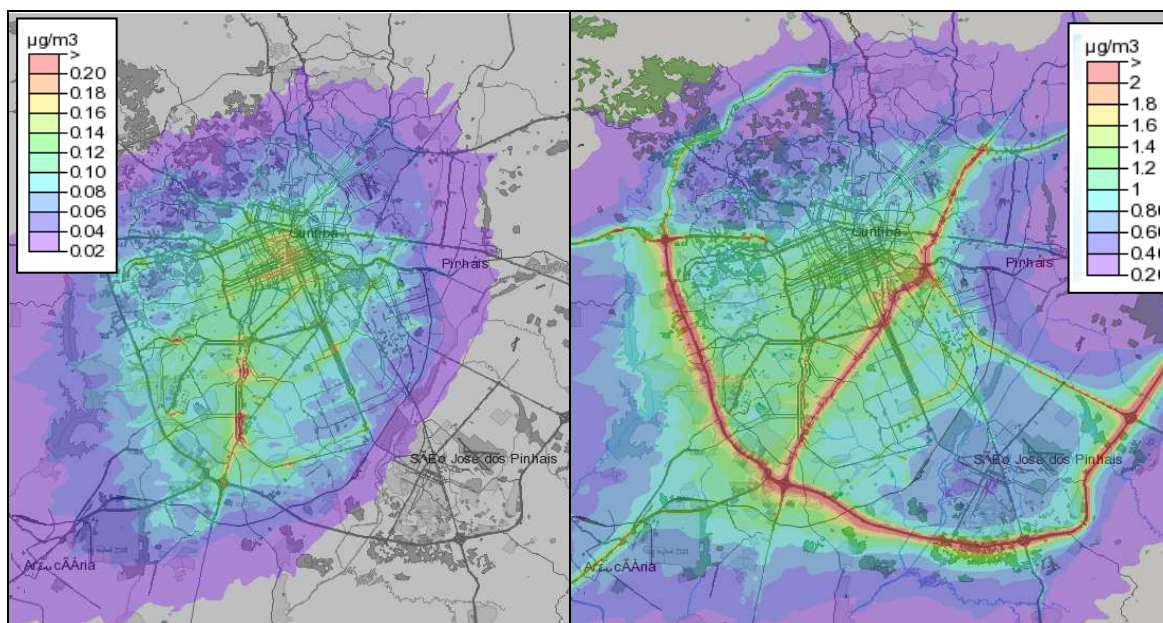


Figure 4.4.16 Simulated average BC contribution 25th July – 24th August 2016 from public transport (upper left) and private traffic (upper right). Note color different scales! Bus emissions corrected with factor 1.2 and private traffic with factor 5.0, according to comparison with measurements in the Marechal Deodoro street canyon.

As for the impact of local **BC** sources (Fig. 4.4.16), we have only inventories of the road transport sector. Here private traffic is very dominating since the emission factors suggested after the regression analysis indicated a factor 1.2 for buses and a factor of 5 for private traffic.

Local BC emissions contributing to simulated concentrations as in Fig. 4.4.16, are sector distributed as:

- Public transport (buses): 17.5 tons/year
- Private traffic: 374.5 tons/year

Simulated PM_{2.5} and BC levels in street canyons

The results of the bike monitoring along one of the routes – here called S1 (Fig. 4.4.17) – have been compared to model simulated impacts of public transport (buses) and private vehicles. Since the street canyon model used, OSPM, is very sensitive to input of geometrical data like street width and heights of the buildings, we used laser scan data from the city center, provided by IPPUC, to describe the geometrical conditions along the S1 route. IPPUC also contributed with estimations of traffic volumes for the streets of the S1 route, see Fig. 4.4.18.

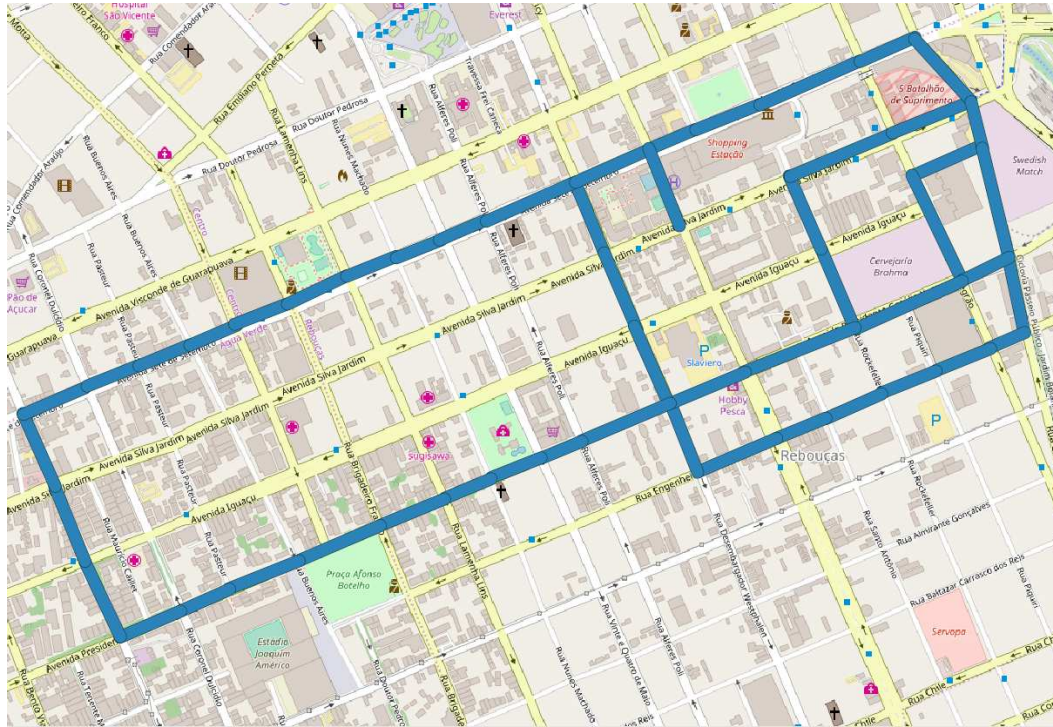


Figure 4.4.17 The S1 route as it was simulated (the biking route was a bit more extended).

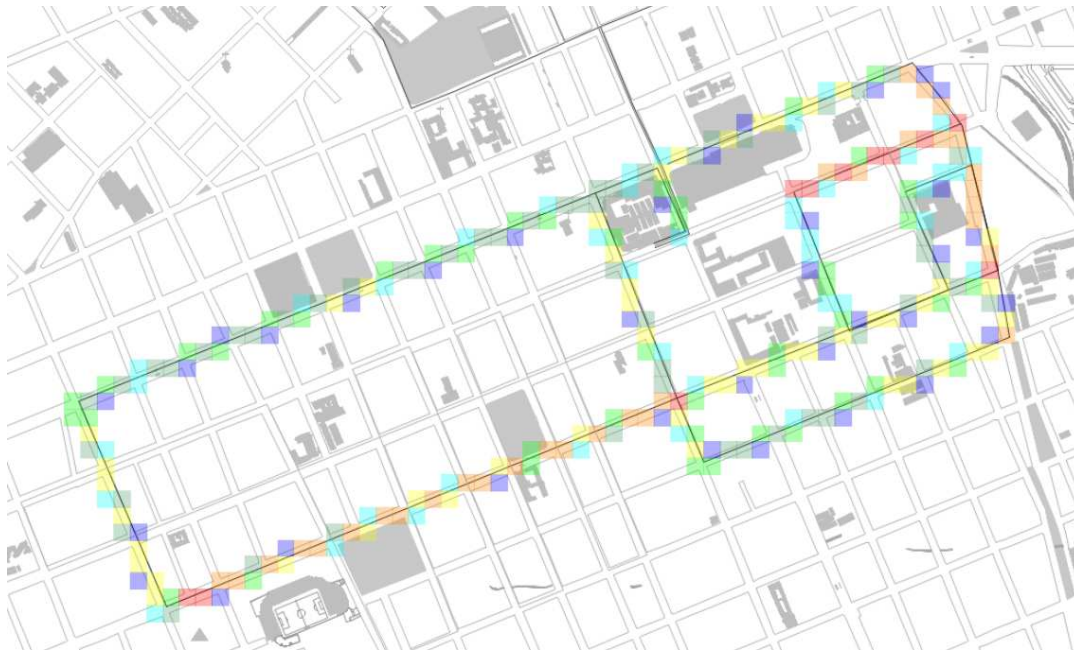


Figure 4.4.18 Traffic volumes on a relative scale, where red color indicate volumes > 31000 veh/day. Maximum traffic intensity is found on Silva Jardim with 39000 veh/day. Public transport (buses) are found on all streets, except Tv. Pinheiro and Engenheiros Rebouças, according to the inventory.

There are four data sets collected by the bikes, all yielding momentaneous BC and $PM_{2.5}$ concentrations that have been aggregated to segments (see Section 4.2). Two of the data sets come from morning peak hours during weekdays, one from a Friday afternoon peak hour and finally one from a Sunday morning. We will here focus on the comparison on the BC levels, since for the $PM_{2.5}$ impact there seems to be more

unidentified sources involved. We also dispose hourly background concentrations of BC from the Marechal Deodoro roof level, while PM_{2.5} is only registered as daily values.

Figure 4.4.19 shows the model results for one of the morning peak hours, separating the contribution from buses and private traffic. Overall the impact from buses and from private traffic show similar levels along the S1 biking route, but with different spatial distribution. The public transport shows most impact along Sete de Setembro, while the private traffic impact dominates along Getúlio Vargas. The street canyon model outputs concentrations on both sides of the road link, but in the comparison we will use the mean value of the two sides since we do not know exactly on which side the biking data were collected.

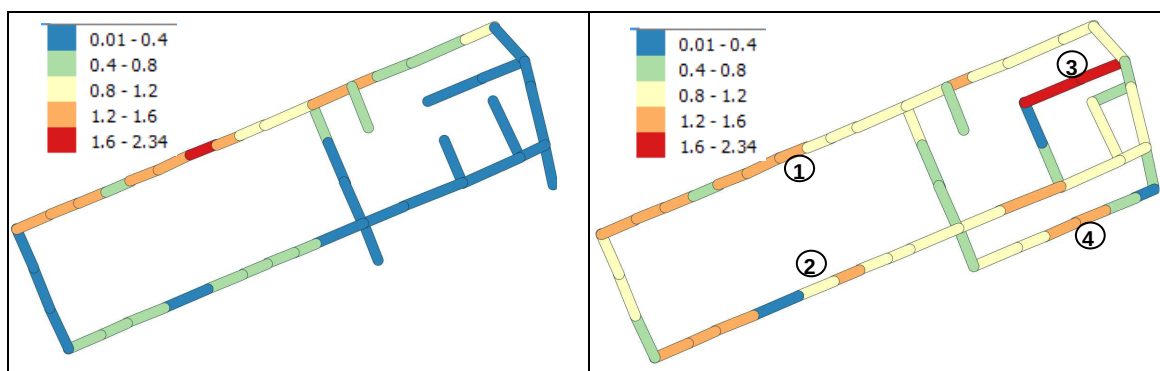


Figure 4.4.19 Local contributions of BC from buses (left) and private traffic (right) on Wednesday morning August 03, between 08 and 10 hours. All levels corrected according to the comparison at the fixed Marechal Deodoro station. There are some streets along S1 route without buses, those streets are not shown. 1 = Sete de Setembro, 2 = Getúlio Vargas, 3 = Silva Jardim and 4 = Eng. Rebouças.

Figure 4.4.20 shows to the left the summed impact of buses and private traffic, with urban background contribution added. To the right the biking data are displayed. For the comparison it should be noted that the model output consist of two averaged hourly concentrations, while biking data are collected with 10 second time resolution. The biking data has been averaged over the time that it took to pass through a specific segment, however they still represent a much higher temporal resolution as compared to the simulated data. With a much higher temporal resolution, around minutes, there will be much higher peak concentrations, as indicated by the upper limit of the red color scale. Excluding these, rather few, extreme concentrations measured by the bikes, the simulated and measured levels show a reasonable similarity. It is also possible to see both in model and measurements the raised BC levels along Sete de Setembro (where buses dominate), in the southwestern part of Getúlio Vargas and the northeastern part of Silva Jardim (where private traffic dominate). However, the model shows low BC levels in the eastern part of Engenheiros Rebouças, while the measurements report high BC during weekdays, indicating a possible underestimation of the traffic volumes along this road.

In summary the BC pollution in the Curitiba center is contributed in similar shares by public transport and private vehicles.

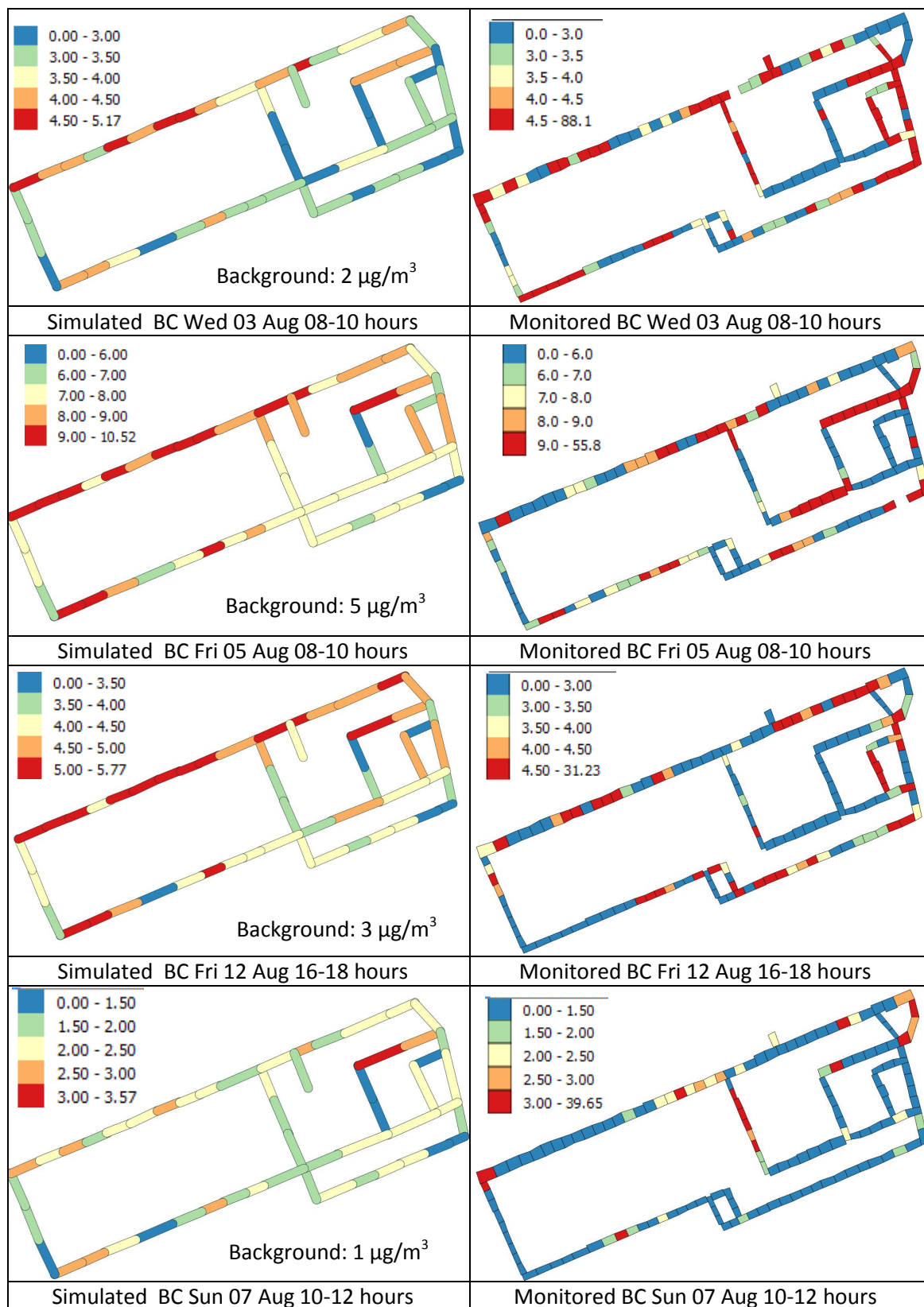


Figure 4.4.20 Local contributions of BC from buses (left) and private traffic (right) for selected days and hours. All levels corrected according to the comparison at the fixed Marechal Deodoro station. Background concentrations taken from Marechal Deodoro roof station.

4.5 Overview of present air quality levels in Curitiba, in comparison to EU air quality directive and WHO recommendations

Figure 4.5.1 gives an overview of the how the present air quality in Curitiba, as revealed by the ParCur phase 1 assessment, compares to the different standards and recommendations. The non-compliance of the EU limit value for **PM₁₀ daily mean** values is illustrated in Fig. 4.5.2.

unit: $\mu\text{g}/\text{m}^3$	PM ₁₀ annual	PM ₁₀ daily	PM _{2.5} annual	NO ₂ annual
Brazilian legislation	50 ✓	150 ✓	-	100 ✓
EU air quality directive	40 ✓	50* !	25 ✓	40 ?
WHO guidelines	20 !	50 !	10 !	40 ?

*expressed as 90th percentile

Figure 4.5.1 Overview of limit values and recommendations for PM₁₀, PM_{2.5} and NO₂ in ambient air. From the results obtained in ParCur phase 1, three indicators have been attributed to each of the reference levels to demonstrate if current levels are compliant or not:

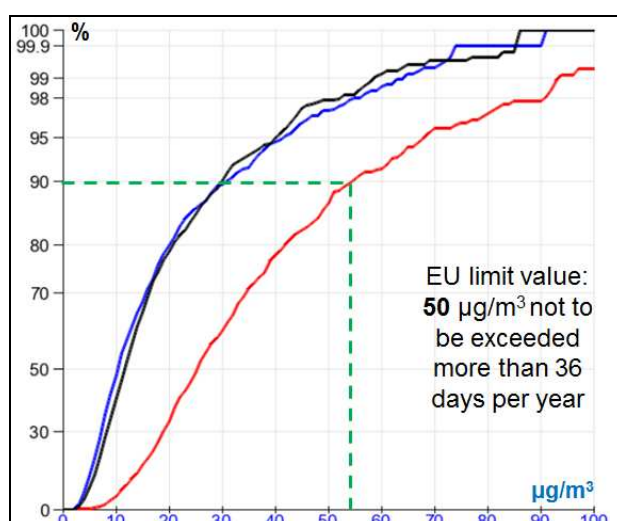
- ✓ = the observed and modelled contrations in Curitiba are compliant
- ? = the observed and modelled contrations in Curitiba are close to the limit value or the recommendation, further assessment should be made to conclude if compliant or not
- ! = the observed and modelled contrations in Curitiba is not compliant

As for **black carbon (BC)**, there are no limit values or recommendations to compare to. The ParCur assessment indicate for Curitiba BC levels in the urban background of the order of **2.0-2.5** $\mu\text{g}/\text{m}^3$. In street canyons with dense traffic the levels are typically doubled, **>5** $\mu\text{g}/\text{m}^3$.

Figure 4.5.2

Frequencies of observed PM10 at IAP stations CIC (red), PAR (black) and BOQ (blue), based on observations 2013-2015.

At CIC the 90-percentile value is about **54** $\mu\text{g}/\text{m}^3$, which is above the EU limit value. The 90-percentiles at PAR and BOQ are at about **30** $\mu\text{g}/\text{m}^3$, i.e. compliant with EU limit values.



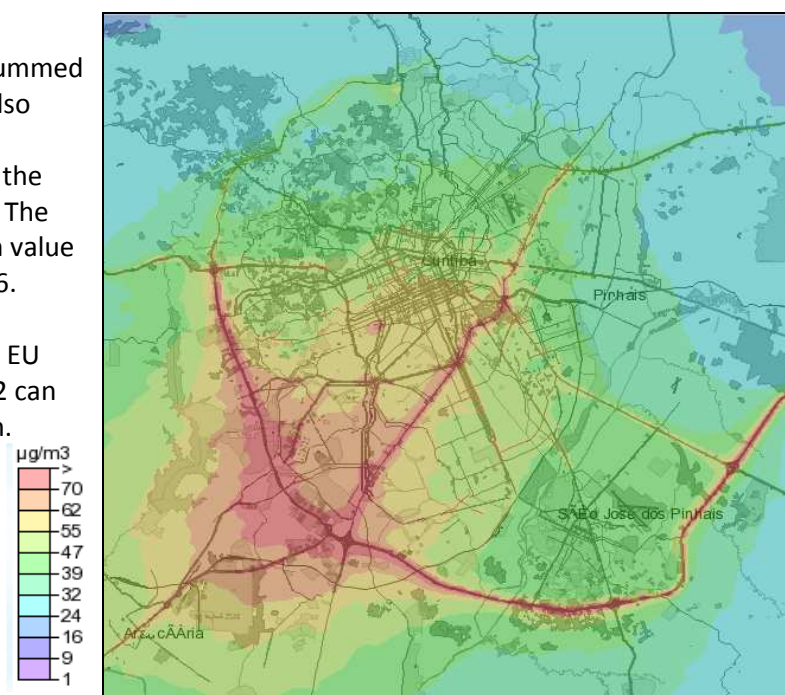
The concern for a possible non-compliance of the EU limit value for **annual NO₂** levels is based on two findings:

- The passive sampling inside the Marechal Deodoro street canyon during the monitoring campaign July-August 2016 revealed two-week averages of 42.6 and 47.9 µg/m³. For a “normal year” this would indicate an annual average well below 40 µg/m³, since July-August are the months with the highest levels. However, as shown in Table 4.2.2, the monitoring period 2016 showed much lower NO₂ levels than in 2013-2015. It is thus not to be excluded that NO₂ levels in street canyon may reach the EU limit value also in the coming years.
- The model simulations of NO_x reveal high levels in the southwestern part of Curitiba, created by the summed impact from the traffic along the ring road and the industrial emissions in Araucária (Fig. 4.5.3). However, the model output is not sufficient for a direct comparison with the EU limit value, since it represents NO_x (not NO₂) and constitutes only an average over one month. However, the NO₂ concentrations in urban background are normally rather close to NO_x levels, so the ParCur recommendation is to consider the possibility of non-compliance with the EU-directive in the southwestern area of the city.

Figure 4.5.3

Simulated NO_x based on the summed local impact (Fig. 4.4.14) and also including the impact from the regional model which includes the Araucária industrial emissions. The simulation illustrates the mean value for 25th July – 24th August, 2016.

It can not be excluded that the EU limit value of 40 µg/m³ for NO₂ can be reached, as an annual mean.



Stretching the comparison of the present Curitiba air quality levels also to the recommendations made by WHO, there are concerns for **PM₁₀ annual average** levels (Fig. 4.5.4), not only as demonstrated earlier for daily averages (Fig. 4.5.2). The IAP station at CIC shows PM₁₀ levels above the WHO recommended level of 20 µg/m³ as an annual average.

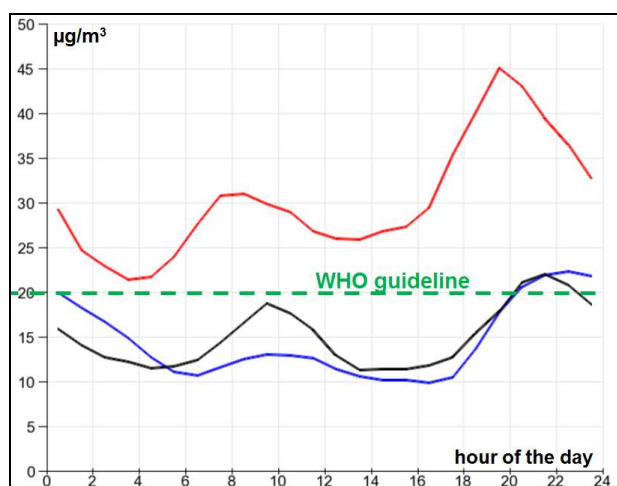
Figure 4.5.4

Annual PM_{10} averages for each hour of the day, observed at IAP stations CIC (red), PAR (black) and BOQ (blue), based on observations 2013-2015.

Annual averages of PM_{10} :

- CIC: **30.3** $\mu\text{g}/\text{m}^3$
- PAR: **15.1** $\mu\text{g}/\text{m}^3$
- BOQ: **14.5** $\mu\text{g}/\text{m}^3$

which can be compared to the WHO recommended value of **20** $\mu\text{g}/\text{m}^3$.



For $PM_{2.5}$ the WHO recommendation or guideline is at only 10 $\mu\text{g}/\text{m}^3$ as an annual average. The only annual-long data set for $PM_{2.5}$, registered within the UFPR campus, showed a $PM_{2.5}$ level just above 10 $\mu\text{g}/\text{m}^3$. However, the month-long $PM_{2.5}$ measurements made at Sitio Cercado during the monitoring campaign, revealed considerably higher levels. Filter data showed an average of 34.8 $\mu\text{g}/\text{m}^3$, the optical instrument indicated 25.3 $\mu\text{g}/\text{m}^3$. The difference can partly be explained by the fact that the some daily filters could not be analysed, see Fig. 4.5.5.

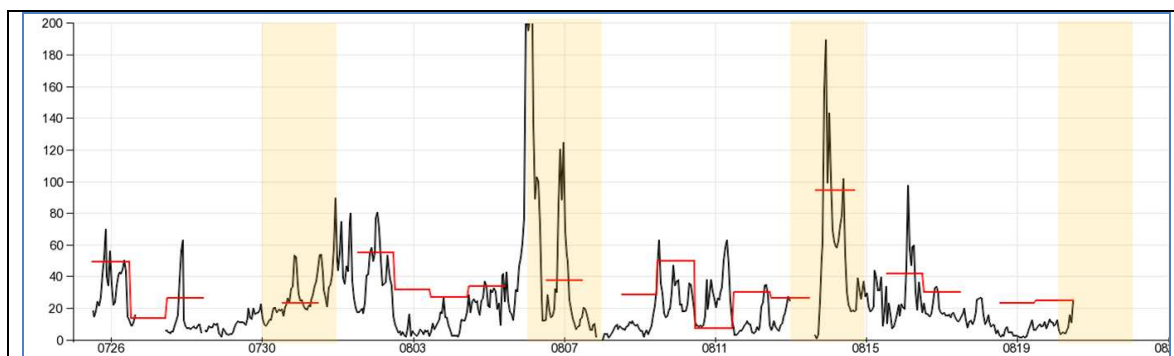


Figure 4.5.5 $PM_{2.5}$ measured at Sitio Cercado 25th July – 20th August, 2016. Daily average values from filter samples (red) gave a mean of 34.8 $\mu\text{g}/\text{m}^3$ and the hourly data registered by the DustTrak sampler gave a mean of 25.3 $\mu\text{g}/\text{m}^3$.

The $PM_{2.5}$ data collected at Sitio Cercado indicate the presence of sources to $PM_{2.5}$, which have little or no impact on the urban background levels in the city center. Clearly the compliance of the WHO guideline for $PM_{2.5}$ is a challenge for Curitiba of today. Fig. 4.5.6 also illustrate the need to lower traffic emissions along the central street canyon corridors, if air pollution levels should come closer to the WHO recommend levels.

Marechal Deodoro
25 July – 29 August, 2016

*Note: monitor data
from 1 month*

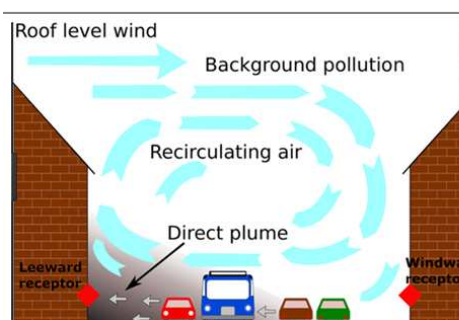


Figure 4.5.6 Overview of how local traffic can increase air pollution levels inside a street canyon in Curitiba, adding to the urban background levels registered at roof level. Measurements made in the Marechal Deodoro street canyon. *Note:* The photo is from another street, used for illustrating how the buildings contribute to a canyon-like structure with reduced ventilation (also illustrated in the figure to the left).

5 Conclusions

The analysis of existing air quality data and the results of the ParCur wintertime monitoring/modeling campaign 2016 gives the following main conclusions:

- The air quality in Curitiba comply with existing Brazilian regulation concerning PM_{10} and NO_2 . A comparison with European air quality standards shows that daily PM_{10} values at the IAP CIC station exceeds the EU limit values. The wintertime monthly averages of NO_2 in a street canyon and $PM_{2.5}$ in one residential area obtained during the ParCur campaign indicate possible exceedances for the annual standards, however this should be more carefully analyzed through long-term measurements covering at least one year.
- There is a relatively large contribution to NO_x levels coming from sources southwest of the Curitiba municipality, mainly from the Araucária area, that is superimposed upon the high traffic impact along the ring road. Model simulations reveal typical wintertime urban background NO_x values of 40-70 $\mu g/m^3$, of which at least half originates from sources outside the Curitiba municipality, most linked to the industrial sector.
- Urban background levels of BC are fairly homogeneously distributed over Curitiba with a wintertime mean concentration of about 2-2.5 $\mu g/m^3$, of which half comes from local traffic exhausts. There is no emission inventory of industrial contributions to BC, but it is likely that a considerable part of the remaining contribution comes from industrial sources outside the Curitiba municipality.

BC is not regulated, but local traffic contributes to high concentrations in traffic environments, typically doubling the urban background concentrations. Present BC levels in Curitiba are comparable to historic levels registered e.g. in Stockholm some 10-15 years back. In Sweden these levels have been strongly reduced during the last 10 years and a similar development should be possible in Brazil if vehicle technology can be improved.

- While BC urban background concentrations are homogeneously distributed over Curitiba, there are strong gradients in $PM_{2.5}$ over at least some parts of the city. Urban background $PM_{2.5}$ levels are fairly low in the city center, in line with the WHO recommended levels, but measurements in a residential area in southern Curitiba indicate a strong impact of some unknown local sources. An analysis of the elemental and organic carbon fractions of the particles sampled in this residential area, indicate the possibility that wood or biomass combustion takes place there. Within this residential area, the $PM_{2.5}$ levels obtained during one month indicate an annual average exceeding the WHO recommendations.

6 Suggestions for future work

Based on the main conclusions of the ParCur first diagnostic phase, the following suggestions are given:

- As part of the plan for defining new air quality limit values in Paraná, install a couple of PM_{2.5} monitors to obtain a full year of data. Also NO₂ should preferably be followed for a full year in the locations where ParCur has indicated high levels (in highly trafficked street canyons and in the southwestern part of the city where industrial emissions are high).
- Assess the possibility of lowering the population exposure to harmful pollutants in traffic environments, e.g. by improved vehicle technology and more sustainable mobility systems. The second phase of the ParCur project offers a possibility to evaluate some future transport solutions and their impact on PM_{2.5}, BC and NO_x levels.
- Through inspections, interviews and/or questionnaires investigate the possible existence of combustion sources around Sitio Cercado, contributing to high PM_{2.5} and organic carbon levels. There are possible ways of reducing, in the short term, the impact of wood combustion through information of better practices, e.g. using dry wood and sufficiently provision of oxygen to the combustion process. If the combustion takes place in heating and/or cooking devices, a regulation and/or stimulation to switch to better technology can also be made. Residential waste burning in open air should preferably be regulated and controlled.
- Assess the possibility of lowering the pollution contributions of NO_x, PM₁₀ and BC from the industrial sources outside the Curitiba municipality. This can be made by identifying the largest emission sources and evaluate if better technologies can be used to lower the impact.

Note that these suggestions are given with the purpose to lower population exposure to long-term air pollutants that are affecting the health and to assure compliance of a future stricter legislation that is expected to be defined for the Paraná state. As stated in the conclusions, air pollutant concentration levels in Curitiba comply with the current Brazilian legislation. A second purpose of the suggestions is also to mitigate the emissions of black combustion particles (BC) that affect the regional climate and forms part of the so called Short-Lived Climate Pollutants (SLCPs).

7 Acknowledgements

The authors of this report deeply acknowledge the strong support given by the Curitiba municipality, represented by Rosanne Kupka and Marcelo Misael (ARIN up to 2016), and by Rodolpho Zannin Feijó and Guilherme Zuchetti (ARIN from 2017).

We also acknowledge data, comments and advices given by ParCur participants not listed as authors, but who participated in workshops and meetings during the first phase of the project. This numerous group includes representatives from the UP and PUCPR universities, other municipal departments than URBS and IPPUC, Swedish contacts from KTH and the Swedish EPA. We finally acknowledge the air quality group from Instituto de Energia e Meio Ambiente (IEMA) from São Paulo that has attended and contributed to ParCur workshops. IEMA is a non-governmental organization that technically supports Brazilian states on urban environmental issues related to air quality and energy.

8 References

- Alonso, M. F., Longo, K. M., Freitas, S. R., Fonseca, R. M., Marecal, V., Pirre, M., Gallardo, L., 2010. An urban emissions inventory for South America and its application in numerical modeling of atmospheric chemical composition at local and regional scales. *Atmospheric Environment*, 44, 5072-5083.
- Berkowicz, R., 2000. OSPM – a parameterised street pollution model. *Environmental Monitoring and Assessment*, 65, 323-331.
- Berkowicz, R., Prahm, L. P., 1982. Evaluation of the profile method for estimation of surface fluxes of momentum and heat. *Atmos. Environ.* 16, 2809-2819
- Birch M.E., 2003. Elemental carbon (diesel exhaust): Method 5040, Issue 3, in: *NIOSH Manual of Analytical Methods*, National Institute of Occupational Safety and Health, Cincinnati, OH.
- Bond, T.C., Doherty, S.J., Fahey, D.W., Forster, P.M., Berntsen, T., De Angelo, B. J., et al., 2013. Bounding the role of black carbon in the climate system: A scientific assessment. *Journal of Geophysical Research*, 118, 5380-5552
- Brantley, H.L., Hagler, G.S.W., Kimbrough, E.S., Williams, R.W., Mukerjee, S., Neas, L.M., 2015. Mobile air monitoring data-processing strategies and effects on spatial air pollution trends. *Atmos. Meas. Tech.*, 7, 2169-2183.
- Castelhana, F., Roseghin, 2017 (manuscript to be published)
- Crassier, V.; Syhre, K.; Tulet, P.; Rosset, R., 2000. Development of a reduced chemical scheme for use in mesoscale meteorological models, *Atmospheric Environment*, 34, 2633–2644.
- Danard, M., 1977. A simple model for mesoscale effects of topography on surface winds. *Monthly Weather Review*, 99, 831-839
- Danni-Oliveira, I. M., Mendonça, F., 2007. Noções básicas e climas do Brasil. São Paulo: Oficina de Textos.
- Djouad R., Sportisse B., Audiffen N., 2002. Numerical simulation of aqueous phase atmospheric models: use of a non-autonomous Rosenbrock method. *Atmospheric Environment*, 36(5), 873-879.
- Erlich, C., Noll, G., Kalkoff, W.-D., Baumbach, G., Dreiseidler, A., 2007. PM10, PM2.5 and PM1.0 – Emissions from industrial plants – Results from measurement programmes in Germany, *Atmospheric Environment*, 41 (29), 6236-6254.
- Freitas, S. R., Panetta, J., Longo, K. M., Rodrigues, L. F., Moreira, D. S., Rosário, N. E., Silva Dias, P. L., Silva Dias, M. A. F., Souza, E. P., Freitas, E. D., Longo, M., Frassoni, A., Fazenda, A. L., Santos e Silva, C. M., Pavani, C. A. B., Eiras, D., França, D. A., Massaru, D., Silva, F. B., Santos, F. C., Pereira, G., Camponogara, G., Ferrada, G. A., Campos Velho, H. F., Menezes, I., Freire, J. L., Alonso, M. F., Gácita, M. S., Zarzur, M., Fonseca, R. M., Lima, R. S., Siqueira, R. A., Braz, R., Tomita, S., Oliveira, V., and Martins, L. D.: The Brazilian developments on the Regional Atmospheric Modeling System (BRAMS 5.2): an integrated environmental

- model tuned for tropical areas, *Geosci. Model Dev.*, 10, 189-222, <https://doi.org/10.5194/gmd-10-189-2017>, 2017.
- Galvão, R. F. P., 2011. Expansão Urbana e Proteção Ambiental em Metrópoles Brasileiras, 1980-2010, Dissertação de Mestrado, USP.
- Gidhagen, L., Bennet, C., D'Avila Vargas, M., Wiegand, F., Schneider, I. L., Saft, D., Oberherr, A. D., Haubert, F., Kreuning, C., Spohr Nedel, A., Alonso, M., Mariano, G., Krecl, P., Tagle, M., Díaz, X., Oyola, P., 2015. Emissions and impact on air quality of PM and BC in Saporanga, Rio Grande do Sul - field campaign and model assessment 2014. Report available at https://www.smhi.se/polopoly_fs/1.94060!/Menu/general/extGroup/attachmentColHolid/mainCol1/file/Saporanga_report_2014_final.pdf
- Grell G.A., Dévényi D., 2002. A generalized approach to parameterizing convection combining ensemble and data assimilation techniques. *Geophysical Research Letters*, 29(14), 38.1-38.4.
- Hagenbjörk-Gustafsson, A., Tornevi, A., Forsberga, B., Eriksson, K., 2010. Field validation of the Ogawa diffusive sampler for NO₂ and NO_x in a cold climate. *J. Environ. Monit.* 12, 1315–1324.
- Hansen, A.D., Rosen, H., Novakov, T., 1984. The Aethalometer – An instrument for the real time measurements of optical absorption by aerosol particles. *Sci. Total Environ.* 36, 191-196.
- Holtzlag, A. A. M., 1984. Estimates of diabatic wind speed profiles from near surface weather observations. *Boundary Layer Meteorology* 29, 225-250.
- IAP, 2013. Inventário esatdual de emissões atmosféricas de poluentes (MP, CO, NO_x, SO_x) e proposta para revisão e amplicação da rede de monitoramento da qualidade do ar. Report from Instituto Ambiental do Paraná.
- Josse, B. ; Simon, P.; Peuch, V-H., 2004. Radon global simulations with the multiscale chemistry and transport model MOCAGE. *Tellus, B* 56, 339-356.
- Krecl, P., Targino, A.C., Wiese, L., Ketzell, M., Correa, M.P., 2016. Screening of short-lived climate pollutants in a street canyon in a mid-sized city in Brazil. *Atmospheric Pollution Research*, doi:10.1016/j.apr.2016.06.004
- Krecl, P.; Johansson, C.; Targino, A.; Ström, J.; Burman, L., 2017. Trends in black carbon and size-resolved particle number concentrations and vehicle emission factors under real-world conditions. *Atmospheric Environment*, 165, 155-168.
- Krecl, P.; Targino, A.; Johansson, C.; Ström, J., 2015. Characterisation and source apportionment of submicron particle number size distributions in a busy street canyon. *Aerosol and Air Quality Research*, 15, 220-233.
- Longo, K. M., Freitas, S. R., Pirre, M., et al., 2013. The chemistry CATT-BRAMS model (CCATT-BRAMS 4.5): a regional atmospheric model system for integrated air quality and weather forecasting and research. *Geos. Model Devel.*, 6, 1389.
- Longo, K. M.; Freitas, S. R.; Setzer, A.; Prins, E.; Artaxo, P.; Andreae, M. O., 2009. The Coupled Aerosol and Tracer Transport model to the Brazilian developments on the Regional Atmospheric Modeling System (CATTBRAMS) – Part 2: Model sensitivity to the biomass burning inventories, *Atmospheric Chemistry and Physics*, 9, 2843–2861, 2009.

- Maack, R. Geografia Física do Estado do Paraná, 4ª edição, Ed. UEPG, Ponta Grossa, 2012.
- Marple, V. A., Rubow, K. L., 1976. Aerodynamic particle size calibration of optical particle counters. *Journal of Aerosol Sciences*, 7:425, 425-428.
- Marple, V. A., Rubow, K. L., Turner, W. T., Spengler, J. D., 1987. Low flow rate sharp cut impactors for indoor air sampling: design and calibration. *JAPCA*, 37:11,1303-1307.
- NIOSH Manual of Analytical Methods, 4th ed., U.S. Department of Health and Human Services, 1-3, 1994. Ogawa Protocol Version 6, <http://www.ogawausa.com/protocols>.
- Olivier, J.G.J.; berdowski ,J.J.M.. Global emissions sources and sinks. In: Berdowski, J.J.M.; guicherit, R.; heij B.J. (eds.) The climate system, Lisse, The Netherlands. Balkema Publishers/Swets & Zeitlinger Publishers, 2001. p. 33-78. A.A. ISBN 90 5809 255 0.
- Rosário, N. E., Longo, K. M., Freitas, S. R., Yamasoe, M. A., and Fonseca, R. M., 2013. Modeling the South American regional smoke plume: aerosol optical depth variability and surface shortwave flux perturbation, *Atmos. Chem. Phys.*, 13, 2923—2938,doi:10.5194/acp-13-2923-2013.
- Santos, E., 2014. Curitiba, Brazil: Pioneering in developing Bus Rapid Transit and urban planning solutions. LAP Lambert Academic Publishing.
- SMHI, CMMCh, 2014. Impact assessment of PM and BC emissions from residential wood combustion in Osorno, Chile. Report prepared for Ministerio del Medio Ambiente, Gobierno de Chile. Available at https://www.smhi.se/polopoly_fs/1.94057!/Menu/general/extGroup/attachmentColHoId/mainCol1/file/Osorno%20SMHI%20MMA%20Abril2014.pdf
- Targino, A.C., Gibson, M.D., Krecl, P., Rodrigues, M.V.C., Santos, M.M., Corrêa, M.P., 2016. Hotspots of black carbon and PM_{2.5} in an urban area and relationships to traffic characteristics. *Environ. Poll.*, 218, 475-486.
- Targino, A.C., Rodrigues, M.V.C., Krecl, P. et al., 2016. Commuter exposure to black carbon particles on diesel buses, on bicycles and on foot: a case study in a Brazilian city. *Environ. Sci. Pollut. Res.* <https://doi.org/10.1007/s11356-017-0517-x>.
- Teyssède, H.; Michou, M.; Clark, H. L.; Josse, B.; Karcher, F.; Olivié, D.; Peuch, V.-H; Saint-Martin, D.; Cariolle, D.; Attié, J.-L.; Nédélec, P.; Ricaud, P.; Thouret, V.; Van der, A R. J.; Volzthomas, A.; Chéroux F., 2007. A new tropospheric and stratospheric Chemistry and Transport Model MOCAGE-Climat for multi-year studies: evaluation of the present-day climatology and sensitivity to surface processes. *Atmospheric Chemistry and Physics*, 7, 5815-5860.
- Tie, X.; Madronich, S.; Walters, S.; Zhang, R.; Rasch, P.; Collins, W. Effect of clouds on photolysis and oxidants in the troposphere. *Journal of Geophysical Research*, 108(D20), 4642-4664, 2003.
- Tremback, C.; Powell , J.; Cotton , W.R.; Pielke, R., 1987. The forward in time upstream advection scheme: extension to higher orders. *Monthly Weather Review*, 115, 540-555.

- Tripoli, G.J.; Cotton W. R., 1982. The Colorado state university three-dimensional cloud/mesoscale model -- 1982. part i: General theoretical framework and sensitivity experiments. *Journal de Recherches Atmospheriques*, 16, 185-220.
- Walcek, C. J., 2000. Minor flux adjustment near mixing ratio extremes for simplified yet highly accurate monotonic calculation of tracer advection, *J. Geophys. Res.*, 105, 9335–9348, doi:10.1029/1999JD901142.
- Van Ulden, A. P., Holtslag, A. A. M., 1985. Estimation of atmospheric boundary layer parameters for diffusion applications. *J. Climate and Applied Meteorology*, 24, 1196-1207.
- WHO, 2012. *Health effects of black carbon*. Janssen, N. AH., Gerflofs-Nijland, M. E., Lanki, T., Salonen, R. O., Cassee, F., Hoek, G., Fischer, P., Brunekreef, B., Krzyzanowski, M. World Health Organization Regional Office for Europe, Copenhagen.

APPENDIX 1: ParCur consortium and contact persons

Tabela 1. **Project consortium**

<i>Instituição</i>	<i>Nome</i>	<i>Posição</i>	<i>Contato</i>
SMHI Swedish Meteorological and Hydrological Institute	Dr. Lars Gidhagen	Coordenador geral do projeto Coordenador do Dept. de Investigação em Qualidade do Ar	+46 011 495-8531 Lars.Gidhagen@smhi.se
	Dr. Jorge H. Amorim	Dept. de Investigação em Qualidade do Ar	+46 011 495-8531 Jorge.Amorim@smhi.se
UFPR Universidade Federal do Paraná	Prof. Francisco Mendonça	Geografia, Laboratório do Clima Coordenador do projeto no Brasil	+55 41 3361-3478 +55 41 99634933 chico@ufpr.br
	Prof. Ricardo Godoi	Engenharia Ambiental, Laboratório de Análise e Qualidade do Ar	+55 41 3361-3671 rhmgodoi@ufpr.br
	Pesquisador Francisco Castelhano	Geografia, Laboratório do Clima	+55 41 8816-8885 fjcastelhano@gmail.com
	Prof. Wilson Roseghini	Geografia, Laboratório do Clima	+55 41 3361-3244 feltrim@ufpr.br
	Pesquisadora Gabriela Polezer	Engenharia Ambiental, Laboratório de Análise e Qualidade do Ar	+55 41 9660-5968 gabipolezer@gmail.com
UTFPR Universidade Tecnológica Federal do Paraná	Profa. Patricia Krecl	Engenharia Ambiental, Programa Graduação/Mestrado em Engenharia Ambiental	+55 43 3354-9787 patriciak@utfpr.edu.br
	Prof. Admir Targino	Engenharia Ambiental, Programa Graduação/Mestrado em Engenharia Ambiental	+55 43 9920-9787 admirtargino@utfpr.edu.br
	Profa. Erika Pereira Felix	Química Ambiental	+55 41 9920-0212 erikafelix@utfpr.edu.br
	Profa. Valma Martins Barbosa	Gestão de Resíduos	+55 41 9117-3015 valmam7@gmail.com
	Profa. Tatiana Gadda	Planejamento Urbano	+55 41 9207-1093 tatianagadda@utfpr.edu.br
UP Universidade Positivo	Profa. Eliane Vasconcelos	Programa Doutorado/Mestrado em Gestão Ambiental	+55 41 3317-3448 evasconcelos@up.edu.br
	Prof. José Carlos Roccon Filho	Centro de Pesquisas da Universidade Positivo	+55 41 3317-3015 rocon@positivo.com.br
PUCPR Pontifícia Universidade Católica do Paraná	Profa. Fabiana Andreoli	Coord. Eng. Ambiental	+55 41 3271-1877 fabiana.andreoli@pucpr.br
	Prof. Neri Santos	Decano da Escola Politécnica	neri.santos@pucpr.br +55 41 3271-1627

SEPA Swedish Environmental Protection Agency	Ping Højding	Senior Adviser	+46 10 698 1458 ping.hojding@naturvardsverket.se
KTH Royal Institute of Technology	Profa. Semida Silveira	Coordenadora do Projeto "Smart city concepts in Curitiba"	+46 8-790 74 69 semida.silveira@energy.kth.se
SMMA Secretaria Municipal do Meio Ambiente	Marcus Vinicius Loureiro Pius	Dir. Dept. Pesquisa e Monitoramento	+55 41 3350-8035 mpius@smma.curitiba.pr.gov.br
	Guilherme Esquivel	Dept. Pesquisa e Monitoramento	+55 41 3350-9231 gesquivel@smma.curitiba.pr.gov.br
IPPUC Instituto de Pesquisa e Planejamento Urbano de Curitiba	Francisco Caron Malucelli	Mobilidade Viária	+55 41 3250-1491 fmalucelli@ippuc.org.br
	Denise Aparecida Costa		+55 41 3250-xxxx denisecosta@ippuc.org.br
SEPLAD Secretaria de Planejamento e Administração	Ana Castro	Coordenação Estratégica dos Programas Governo Municipal	+55 41 3350-8739 acastro@seplad.curitiba.pr.gov.br
SETRAN Secretaria Municipal de Trânsito	Sandra Mara Volf Eustáquio	Coordenação Mobilidade Urbana	+55 41 3320-2174 seustaquio@setran.curitiba.pr.gov.br
SMS Secretaria Municipal da Saúde	Giselle Pirih	Coordenação Vigilância Sanitária	gpirih@sms.curitiba.pr.gov.br +55 41 3350-9382
	André Pasdiora	Vigilância e Saúde Ambiental	+55 41 3350-9382 apasdiora@sms.curitiba.pr.gov.br
URBS Urbanização de Curitiba S.A.	Elcio Karas	Diretor de Tecnologia de Transportes	+55 41 3320-3246 ekaras@urbs.curitiba.pr.gov.br
	Alyson Wolf	Automotive Engineering Unit Transport Technology Area	+55 41 awolf@urbs.curitiba.pr.gov.br
ARIN Assessoria de Relações Internacionais	Rodolpho Zannin	Head of International Relations, Office of the Mayor Curitiba City Hall	+55 41 3350-8141 +55 41 88749-5006 rfeijo@pmc.curitiba.pr.gov.br
	Tisa Kastrup	Assessoria de Relações Internacionais, Gabinete do Prefeito	+55 41 41 3350-8141 tisakastrup@pmc.curitiba.pr.gov.br
	Guilherme Zuchetti	International Affairs Officer	+55 41 99946-5588 gzechetti@pmc.curitiba.pr.gov.br

SIMEPAR Sistema Meteorológico do Paraná	Reinaldo Silveira	Dept. Meteorologia	+55 41 3320-2013 rsilveira@simepar.br
	José Eduardo Gonçalves	Dept. Meteorologia	+55 41 3320-2013
IAP Instituto Ambiental do Paraná	Ivonete Coelho da Silva Chaves	Diretora de Monitoramento Ambiental e Controle da Poluição - DIMAP	+55 41 3213-3860 ivonete@iap.pr.gov.br
	Dirlene Silva	Dept. Estudos e Padrões Ambientais	+55 41 3213-3860 dirlenecavalcanti@iap.pr.gov.br
DETRANPR Departamento de Trânsito do Estado do Paraná	Juçara Ribeiro	Dept. Tecnologia e Desenvolvimento	+55 41 3361-1257 jucara.ribeiro@detran.pr.gov.br
LACTEC Institutos Lactec	Tania Graff Miranda	Direção de Meio Ambiente	+55 41 3361-6949 +55 41 3361-6021 (fax)
	Eliseu Esmanhoto	Monitoramento Qualidade do ar	eliseuesmanhoto@lactec.org.br
	Karime Dawidziak	Monitoramento Qualidade do ar	karime.piazzeta@lactec.org.br
UFPEL Universidade Federal de Pelotas	Prof. Marcelo Felix Alonso	Faculdade de Meteorologia	+55 53 32757328 marcelo.alonso@ufpel.edu.br

APPENDIX 2

Table A2.1 Location of the monitoring sites from the IAP network and the ones deployed for the ParCur project.

Site	UTM22S (x)	UTM22S (y)
Praça Ouvidor Pardinho (IAP)	673775	7184696
Boqueirão (IAP)	676308	7179290
Santa Cândida (IAP)	679826	7192510
Cidade Industrial (IAP)	666888	7178932
Marechal Deodoro (roof level)	674209	7186253
Marechal Deodoro (street canyon)	674186	7186245
Sítio Cercado (residential)	673697	7173245
SIMEPAR Curitiba (meteorological station)	677919	7184234
Vicente Machado (passive sampling)	672981	7185819
Mercês (passive sampling)	672964	7186403
Xaxim (passive sampling)	675199	7175769
Vila Petropolis (passive sampling)	681913	7192098
Alto da Glória (passive sampling)	675018	7186202
Alto da Rua XV (passive sampling)	675464	7187364
Bairro Alto (passive sampling)	681002	7187333
Batel (passive sampling)	671943	7185068
Cajuru (passive sampling)	679505	7184371

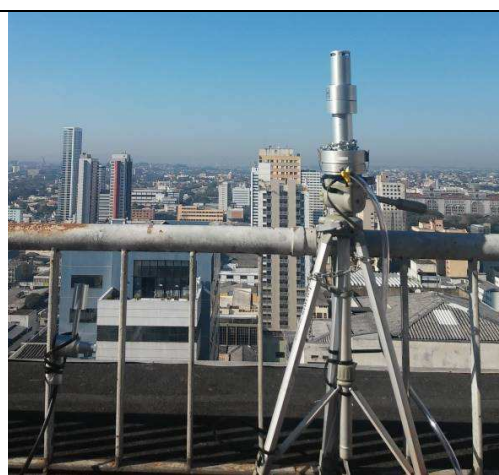


Figure A2.1. Instruments installed at Marechal Deodoro street canyon: street level (at about 3 m height, left) and roof level (about 70 m, right).

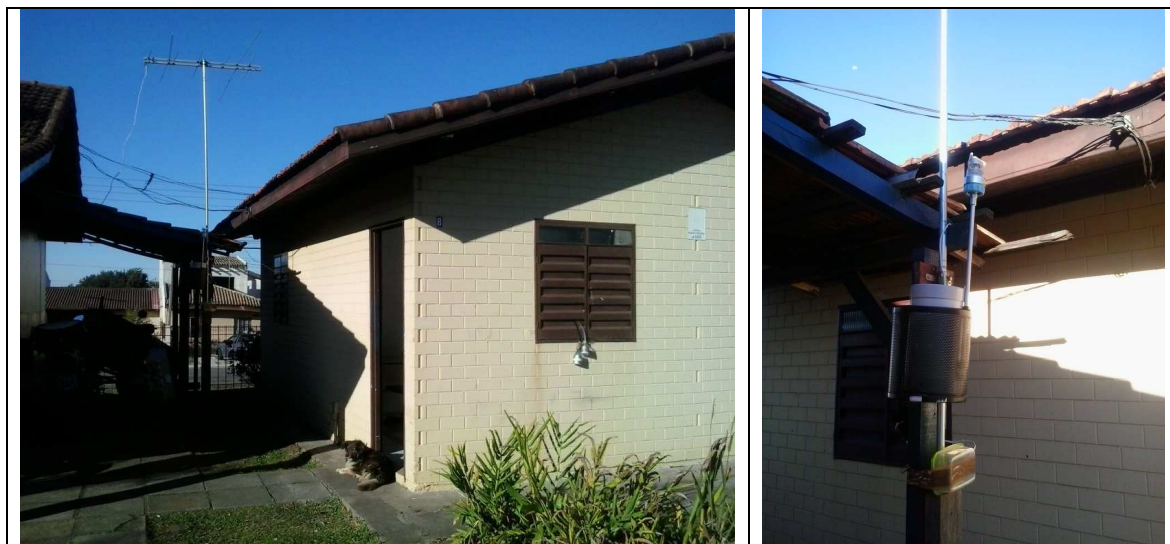


Figure A2.2. Instruments installed at Sitio Cercado, Guarda Municipal office with sampling lines of DustTrak and AE51 through the window (left) and detail of the Ecotech sampler (right).