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

- diagnostic study of current situation (phase 1)

*report elaborated[1] by*


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# CONTENT



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# 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 Healt Organization (WHO) and they do not cover fine particles such as PM2.5 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 5$^{th}$-7$^{th}$ 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 $PM_{10}$ and $NO_2$. 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 $NO_2$ 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 µg/m$^3$, of which half comes from local traffic exhausts. There is no emission inventory of industrial contributions to BC, but is 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 $PM_{2.5}$ 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.

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: µg/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 90$^{th}$ percentile

**Figure ES1** Overview of limit values and recommendations for $PM_{10}$, $PM_{2.5}$ 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 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


**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 $NO_2$ 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 $NO_x$, $PM_{10}$ 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 9$^{th}$ and the 12$^{th}$ 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 Healt Organization (WHO) and they do not cover fine particles such as PM2.5 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, borded 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.

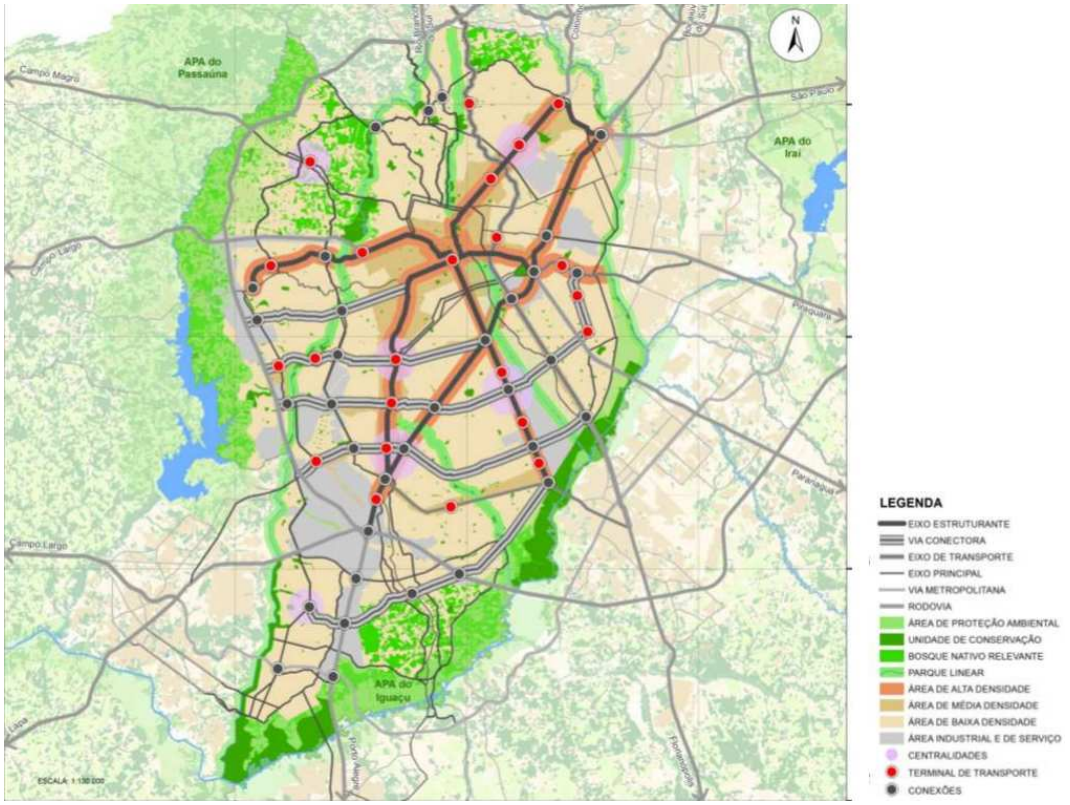



**Figure 2.2.1** Curitiba's structural axes. Source: IPPUC (2014).

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.

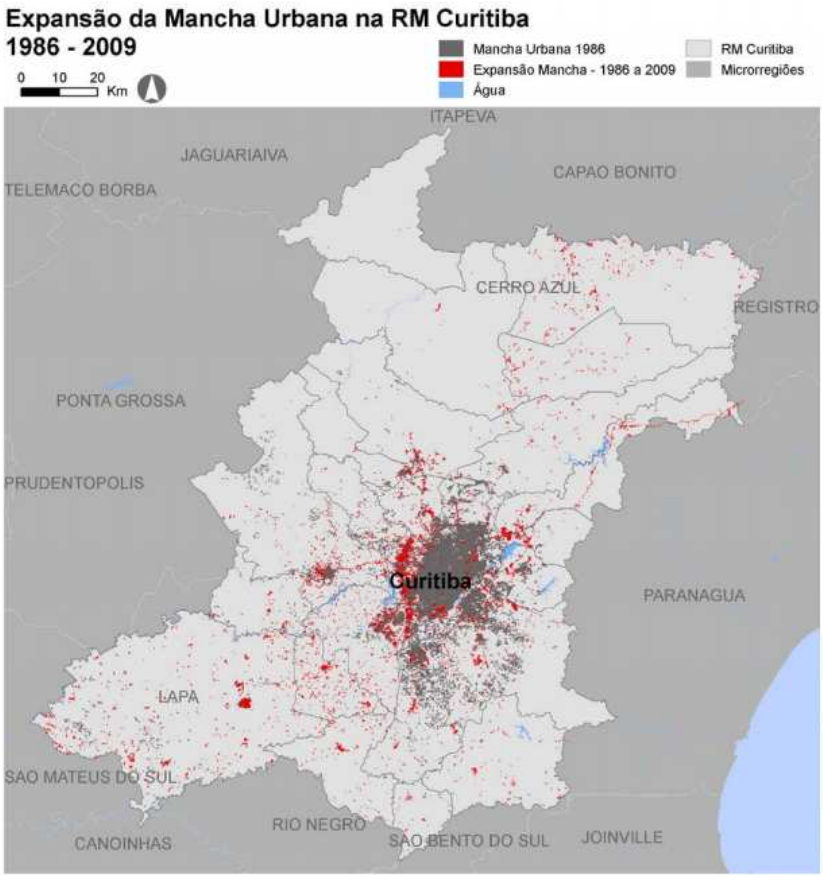



**Figure 2.2.2** Urban area expansion of Curitiba's metropolitan region in 1986-2009. Source: Galvão (2011).

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 ºC).

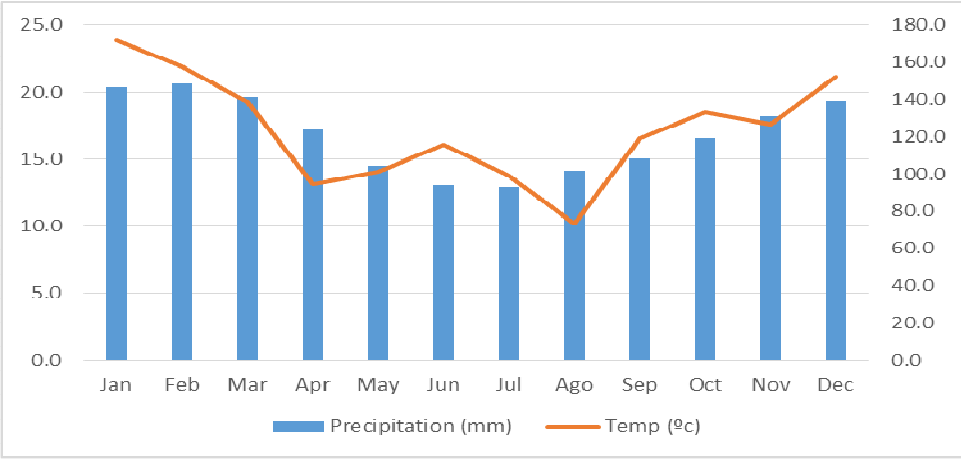



**Figure 2.2.3** Climate normals for Curitiba (1961-1990)

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.

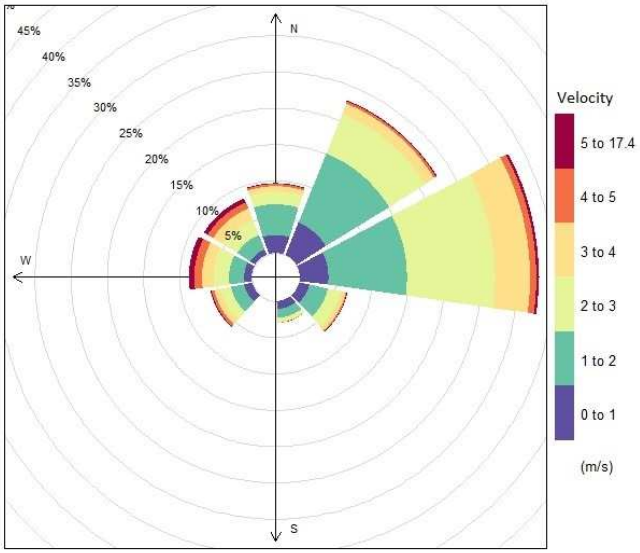



**Figure 2.2.4** – Wind rose for Curitiba (2004 - 2015)

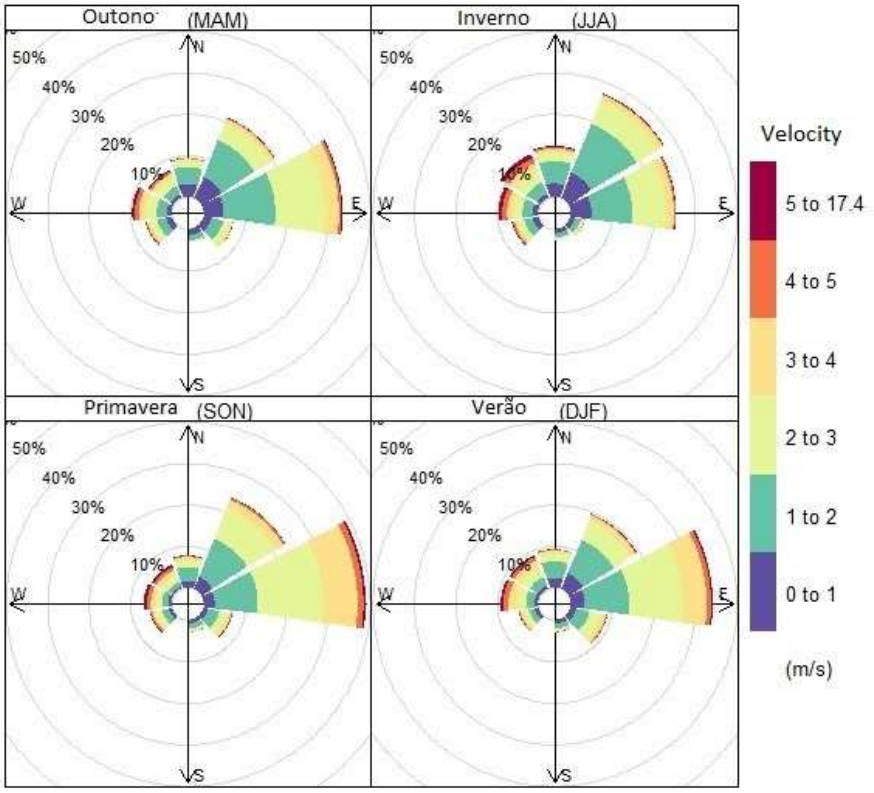



**Figure 2.2.5** – Wind roses for Curitiba divided by season with autumn MAM (upper left), winter JJA (upper right), spring SON (lower left) and summer DJF (lower right) (2004 - 2015)

# 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 PM2.5 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 PM2.5 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 PM2.5 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).

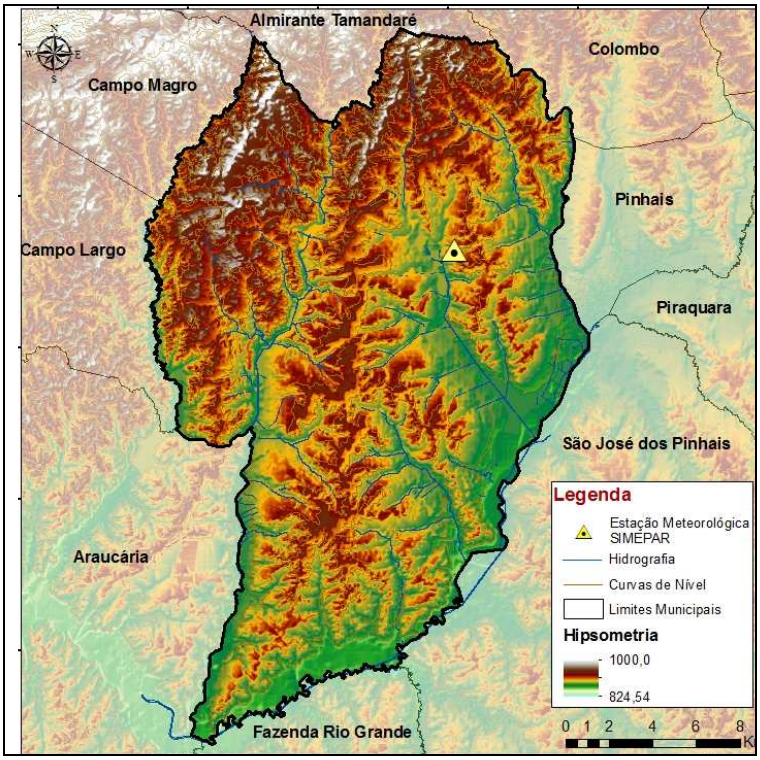



**Figure 3.1**
Topographic map of the Curitiba municipality, with location of SIMEPAR meteorological station.

## 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 Pardinho: 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
- Sitio 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 Petropolis (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

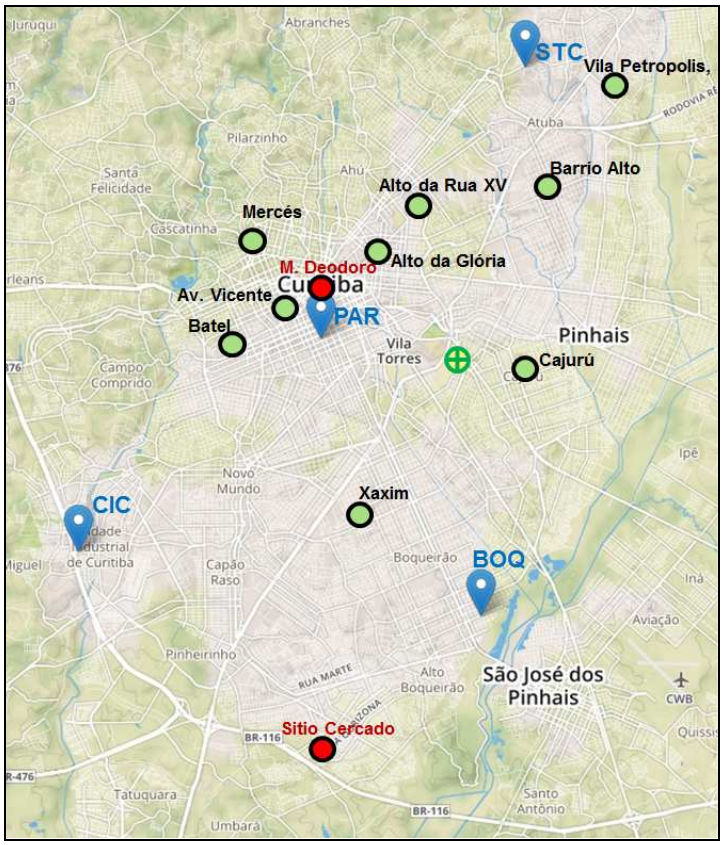



**Figure 3.3.1**
Overview of fixed monitoring stations used in ParCur.

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 $NO_2/NO_x$.

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 $km^2$. 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.

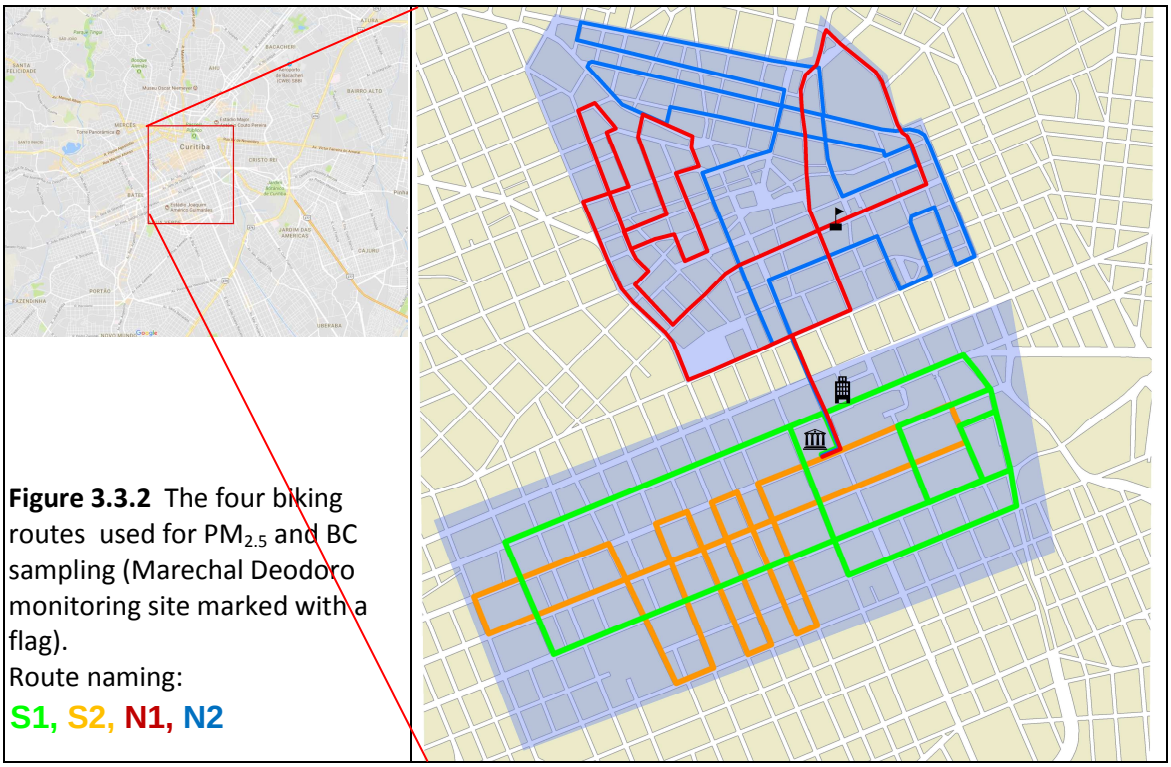


**Figure 3.3.2** The four biking routes used for $PM_{2.5}$ and BC sampling (Marechal Deodoro monitoring site marked with a flag).
Route naming:
**S1, S2, N1, N2**

**PM10 and NOx monitors from the IAP network**

IAP-PAR: Monitors of $PM_{10}$ and NOx. 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 $PM_{10}$. 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 $PM_{10}$ 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 PM2.5 when operated at a flow of 4 LPM (Marple et al., 1987; see Fig. 3.3.3).

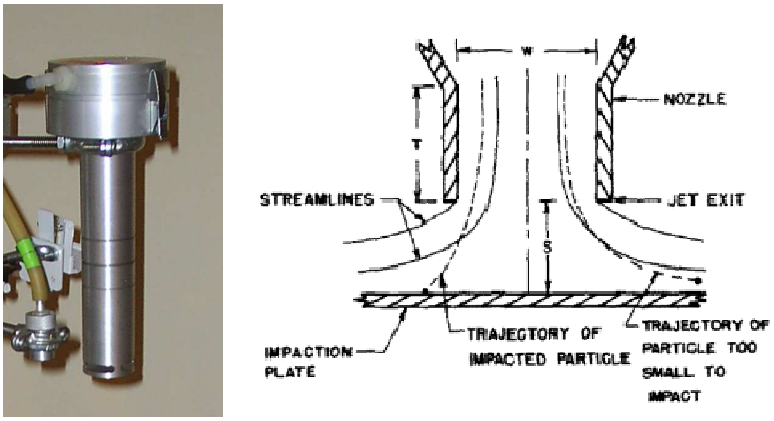



**Figure 3.3.3** Harvard Impactor device for $PM_{2.5}$ (left). Operating diagram of an impactor (right, Marple et al., 1976).

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.

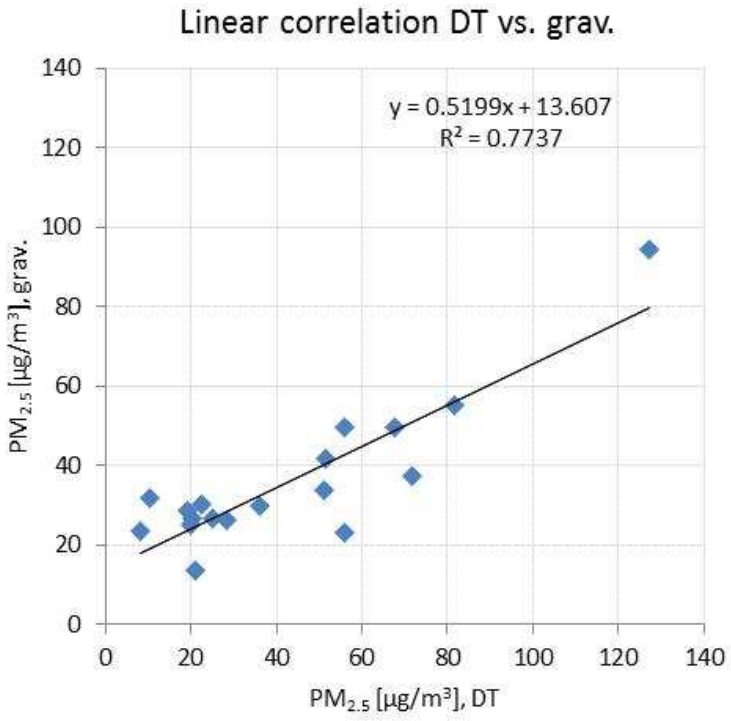
For mass determination, gravimetric analysis was performed on all filters collected at the street canyon and at Sítio Cercado sites following the NIOSH Method 0500, at the UFPR laboratory. Quartz fiber filters were weighted before and after sampling using a ultramicro balance (Sartorius, MAS.7S-000-DF). Before of each weighting, the filters were placed in clean glass Petri dishes and previously conditioned at a temperature of 20 ± 1℃ and at relative humidity of 50 ± 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 ℃, 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 $PM_{2.5}$ 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 µm (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 (ρ = of 2.6 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 PM2.5 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 $\sigma_\lambda$. 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 $\sigma_\lambda$ (18.39 $m^2g^{-1}$) 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 $\sigma_\lambda$ values setup by the corresponding manufacturers.

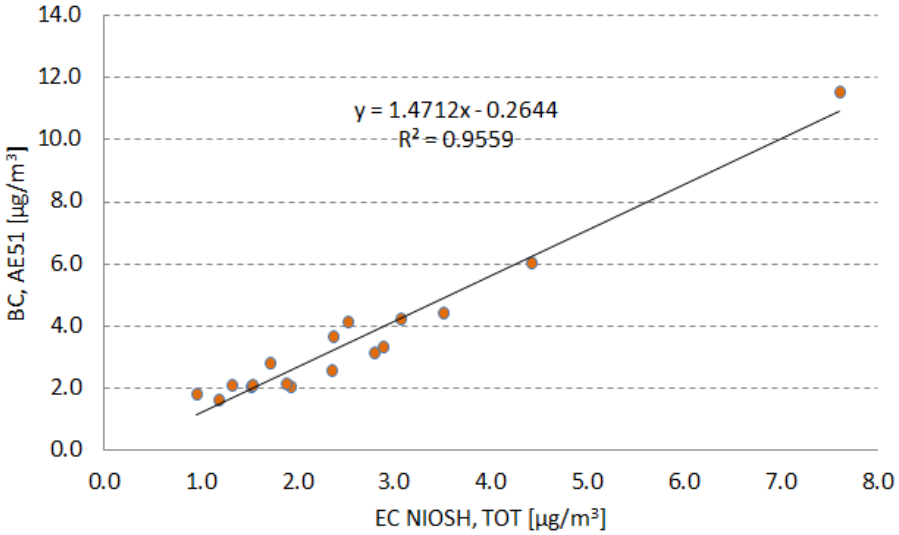



**Figure 3.3.6** Scatterplot comparison of 24-h values of BC (AE51) and EC (TOT) mass concentrations conducted at Sítio Cercado. The solid line represents the least squares line regression; the linear regression equation and coefficient of determination (R2) are also shown.

### 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 $NO_2$/$NO_X$ and analysis

The samplings of $NO_2$ 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 $NO_2$ 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 $NO_2$). 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).

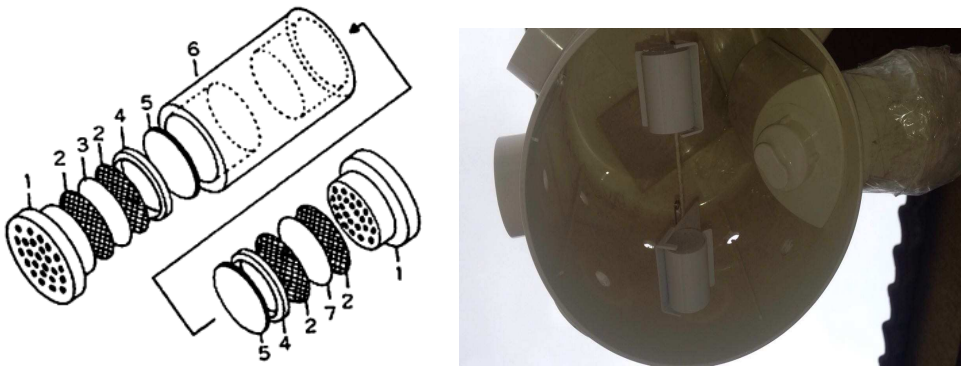



**Figure 3.3.7** Schematic diagram of an Ogawa sampler: (1) diffuser end cap; (2) stainless steel screen; (3) coated $NO_2$ collection filter (14.5 mm in diameter); (4) Teflon ring; (5) Teflon disk; (6) body and (7) coated $NO_x$ collection filter (14.5 mm in diameter) (left, Hagenbjörk-Gustafsson et 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 $NO_2$ determination, it was prepared an analytical curve in triplicate with sodium nitrite standard solutions ranging from 2.0 to 10.0 $\mu g_{nitrite}$ $mL^{-1}$. 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 Pardinho (PAR). The hourly $NO_2$ 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 27$^{th}$ and June 30$^{th}$, 2016, respectively. After comparison, $NO_2$ and $NO_x$ were sampled at ten different places (Fig. 3.3.1) in Curitiba (Centro, Alto da Gloria, 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 29$^{th}$ to August 12$^{th}$, 2016, and the second one from August 15$^{th}$ to 29$^{th}$, 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.

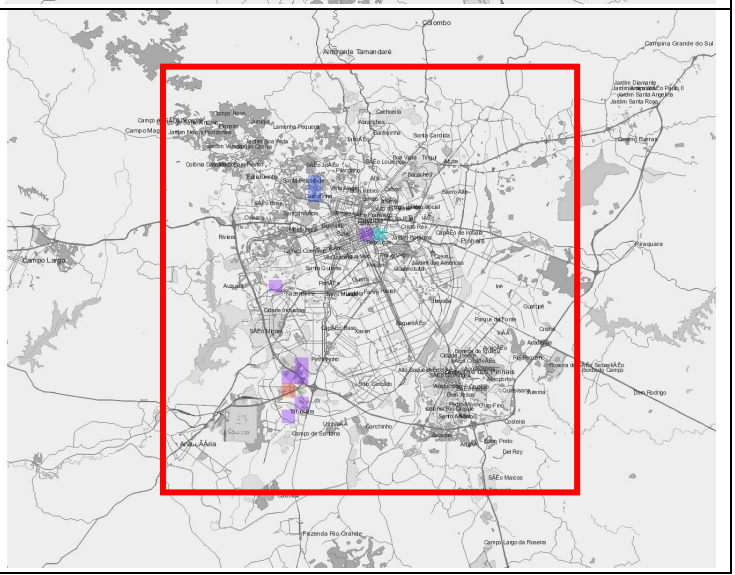
**Figure 3.4.1**
Industrial emissions from the IAP regional emission inventory (2013):

a) all sources inside dispersion model domain:
PM: 2417 tons/year
NOx: 9985 tons/year

b) within Curitiba municipality: (excluding Araucária)
PM: 91 tons/year
NOx: 107 tons/year

**Figure 3.4.2**
Industrial emissions from the SMMA inventory of smaller industries (2013):

all sources inside dispersion model domain:
PM: 470 tons/year
NOx: 160 tons/year



### 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 Empre | Nome Empresa | Código Linh | Nome Linha | Tipo Veículo | Categoria Serviço | Tabe | 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 |

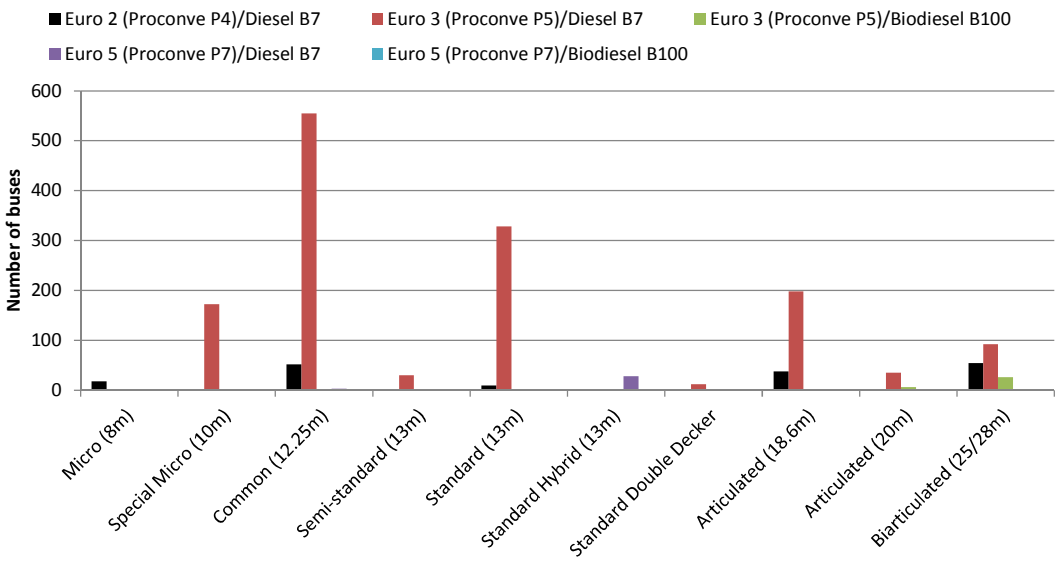



**Fig 3.4.3** Distribution of different bus technologies in Curitiba. In total 1660 buses are in operation.

**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) | (mg/veh,km) | | (mg/veh,km) | | (ml/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).

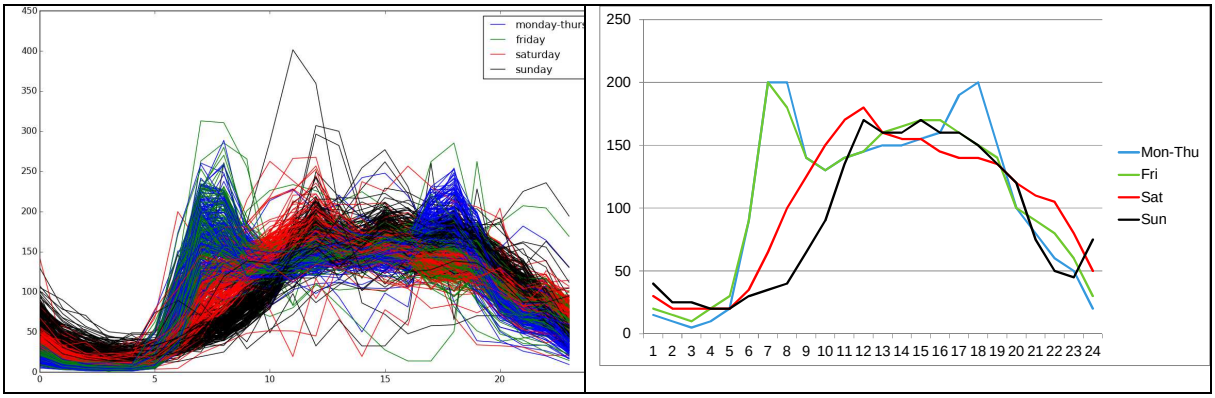



**Figure 3.4.3** Measured traffic volumes from the so called speed traps (speed radar data) at 230 locations. To the left raw data, to the right aggregated time variations for different parts of the week. The temporal variations, as shown to the right, have been normalized for the dispersion simulations.

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 PM2.5 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).

| | **NOx** | **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.

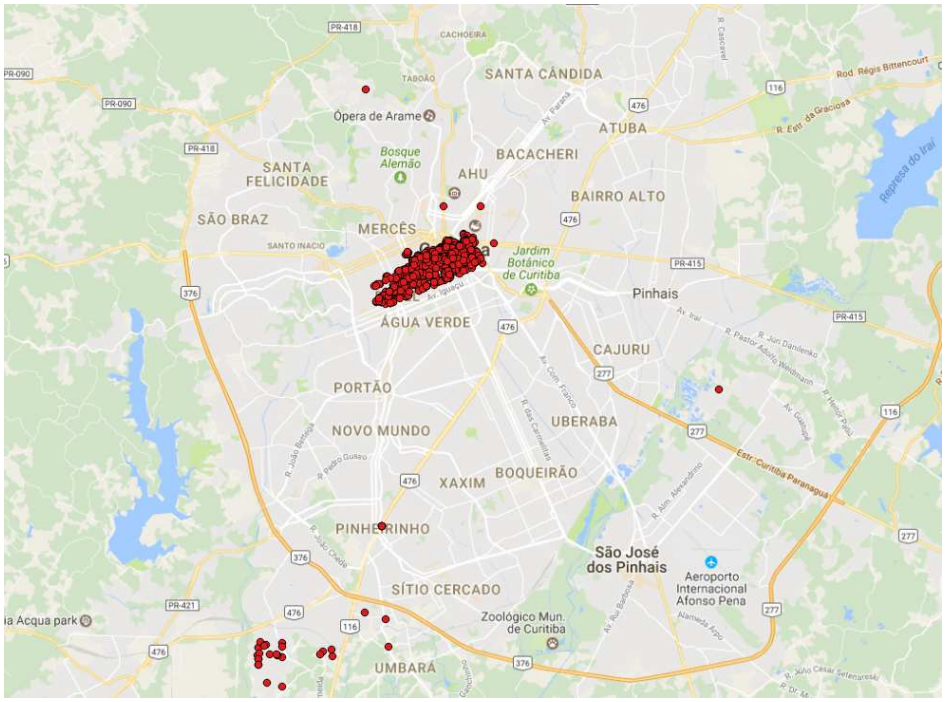



**Figure 3.4.4** Restaurants listed with names, locations found through Google map (only Tatuquara, Centro and Batel districts).

**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 ($CO_2$), methane ($CH_4$) and $NO_x$ and PM2.5) 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 (PM2.5/PM10 = 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<br>(*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; Teyssèdre 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).

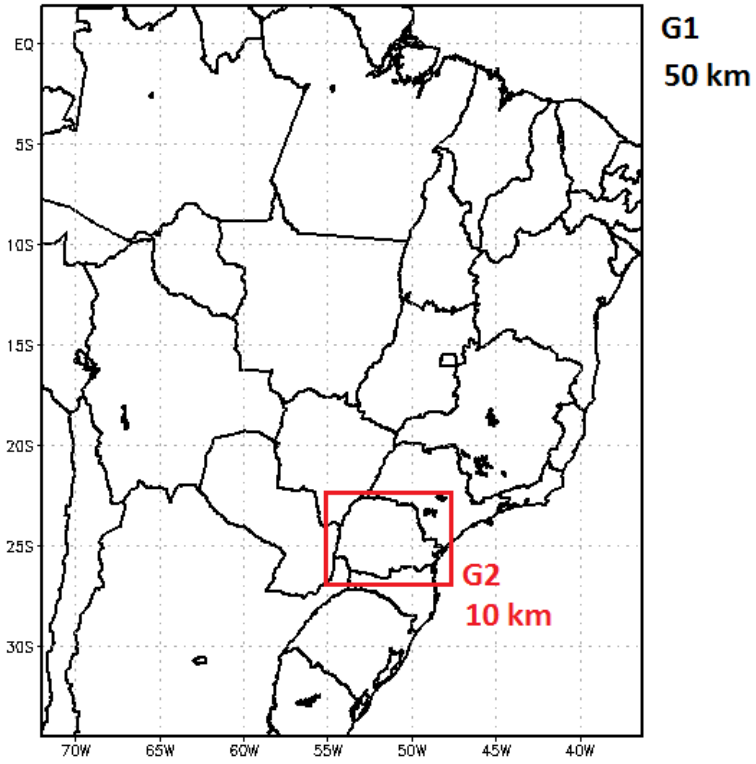



**Figure 3.5.1** Simulations grids for the regional model.

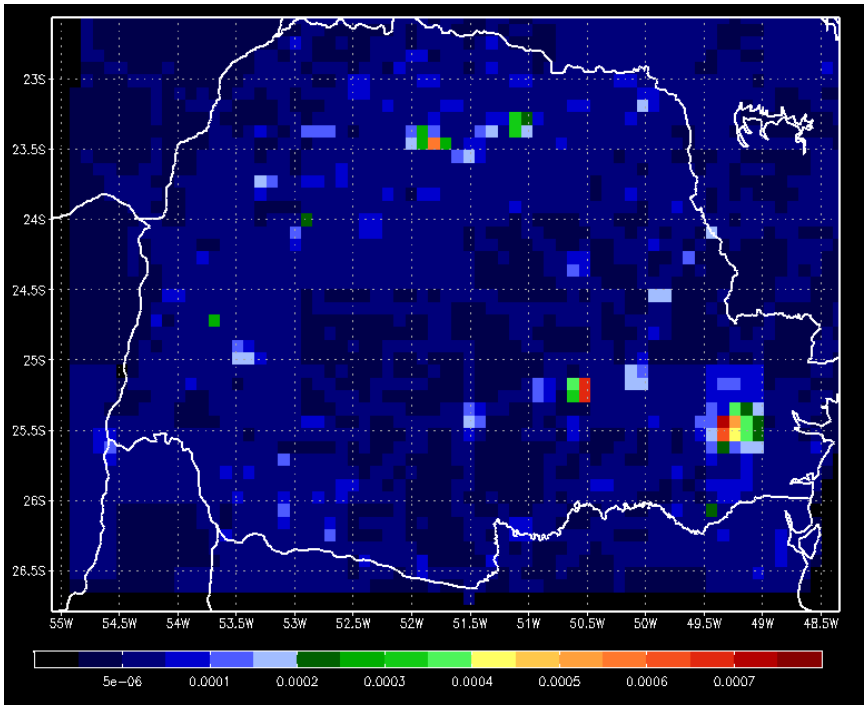



**Figure 3.5.2** Carbon monoxide emission in the finer grid ($kgm^{-2}day^{-1}$)

## 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 $km^2$). 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.

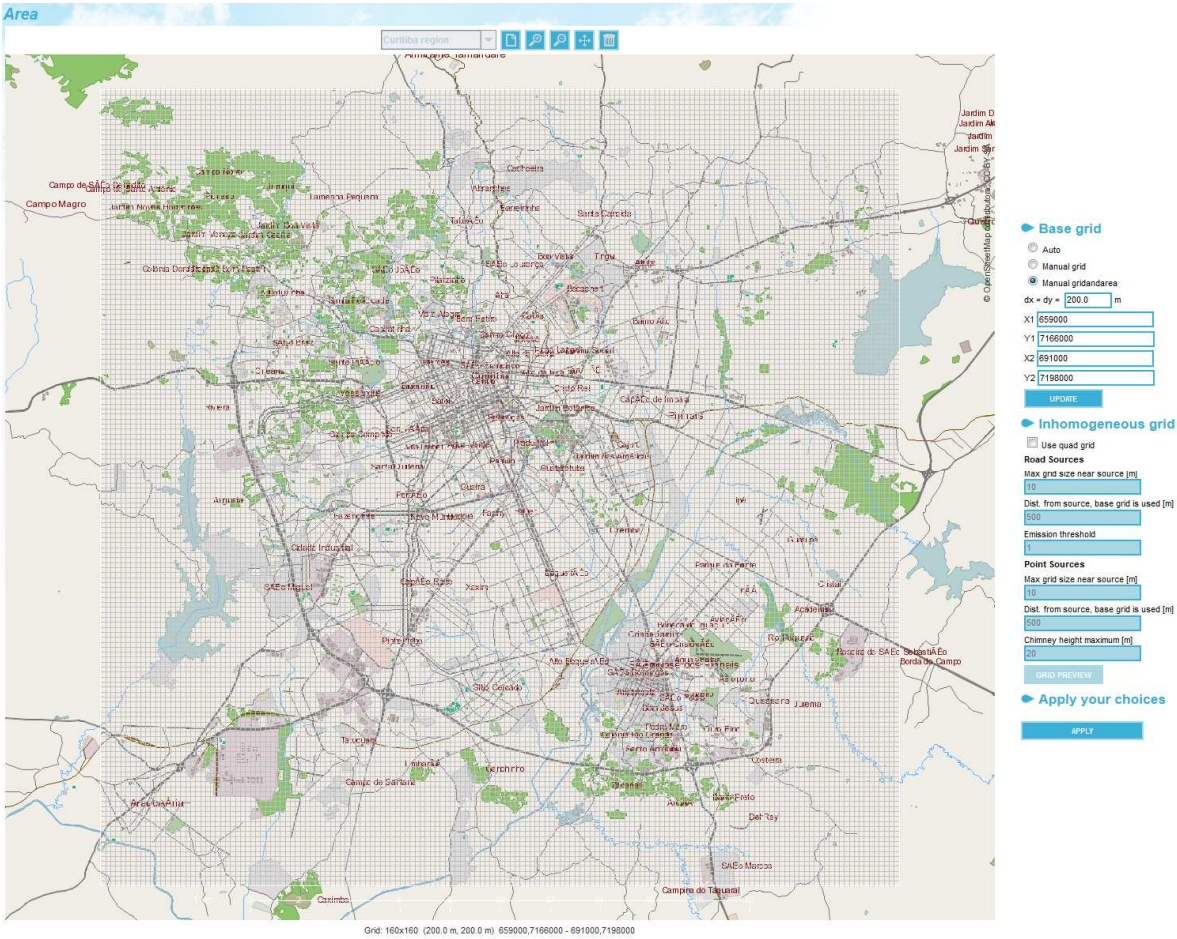



**Figure 3.6.1** Modeling domain and spatial resolution for the wind model and the Gaussian dispersion model.

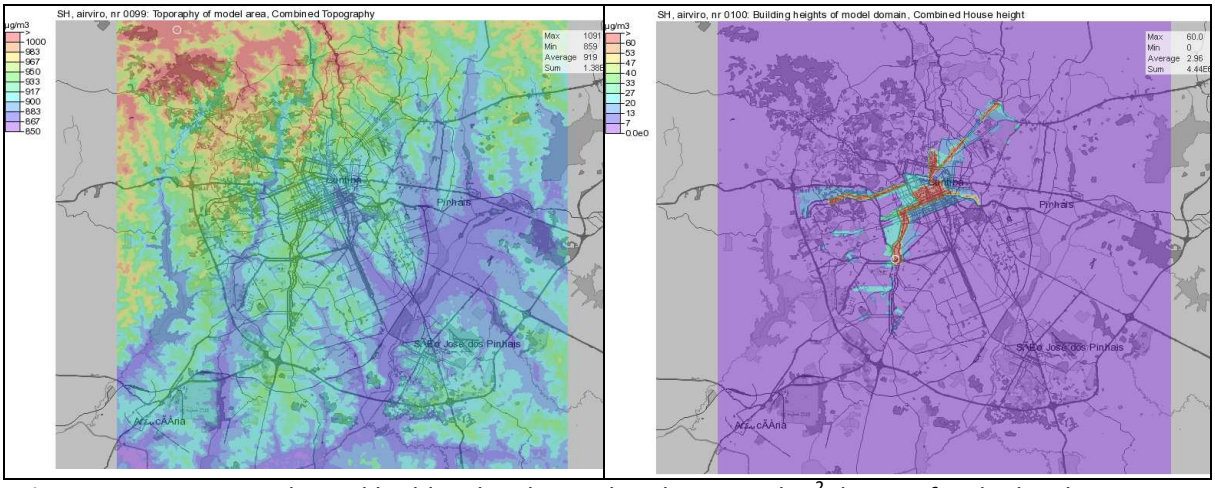



**Figure 3.6.2** Topography and building heights within the 32x32 km$^2$ domain for the local model. The building heights are taken from IPPUC's zoning map of Curitiba.

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.

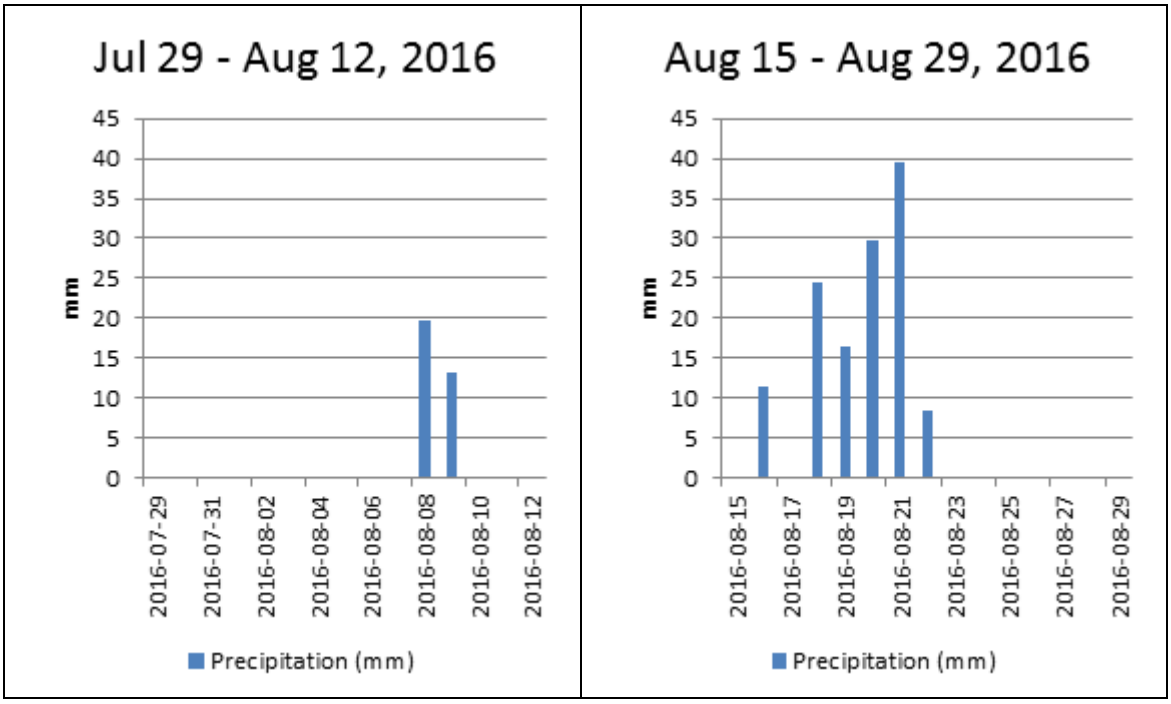



**Figure 4.1.1** Precipitation levels registered during the ParCur monitoring campaign (INMET, 2016)

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, Castelhano 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).

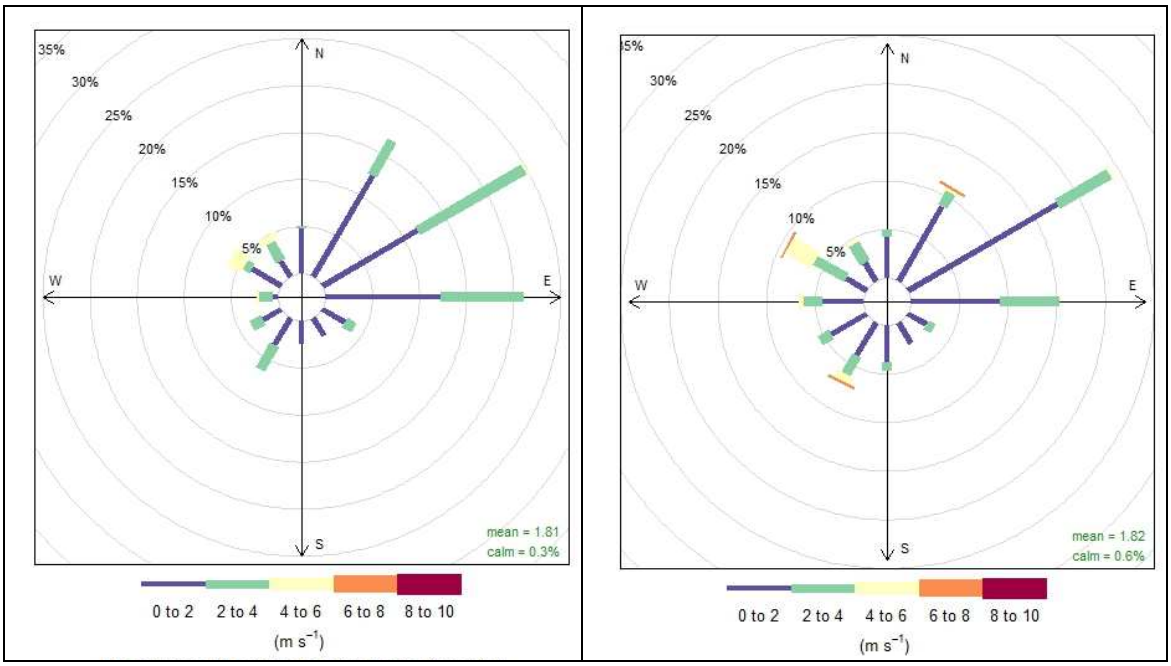



**Figure 4.1.2** Wind speed and direction in Curitiba for the periods of 29/07 to 12/08 (left) and 15/08 to 29/08, 2016 (right).

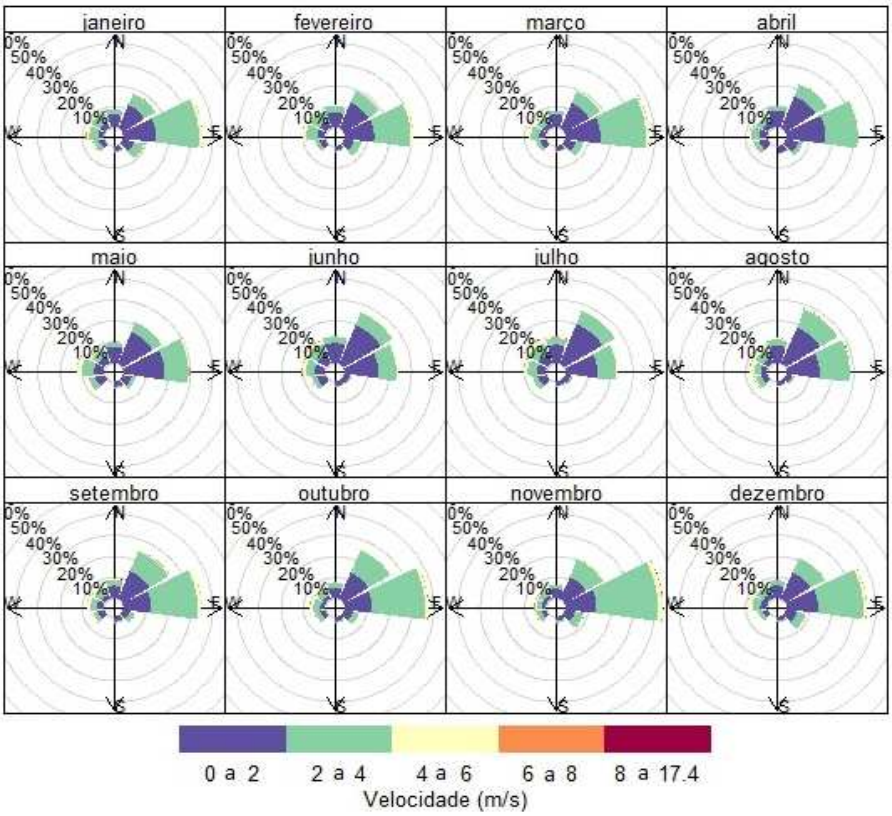



**Figure 4.1.3** Wind speed and direction for Curitiba by month, period 2004 - 2015.

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

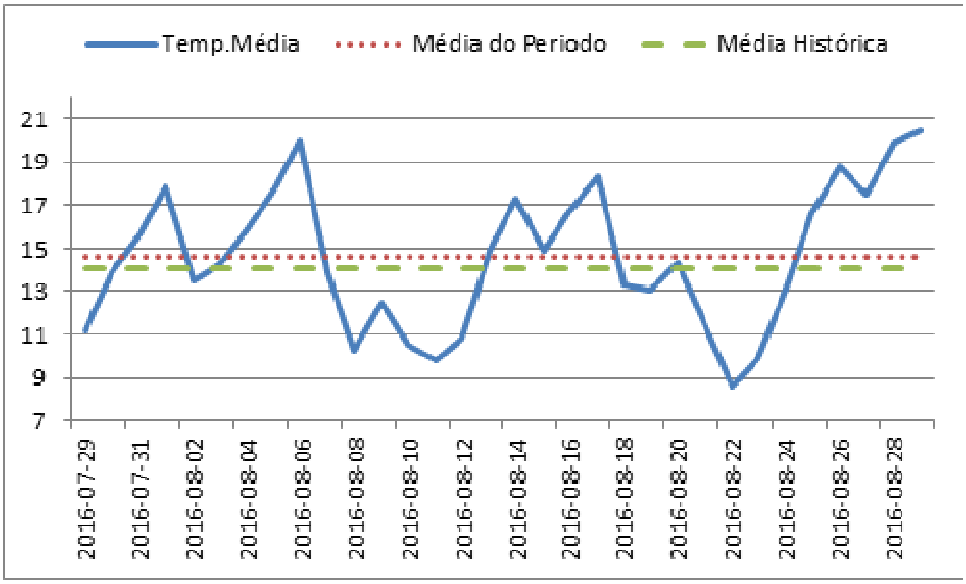



**Figure 4.1.2** Daily average temperature (blue) during ParCur field campaign. Also mean temperatures during the monitoring campaign period in 2016 (red dotted) and the corresponding historical mean temperature for this season (green broken line).

## 4.2 Air Quality monitoring results

### IAP monitoring network

The IAP operational monitoring stations of most interest for assessing $PM_{10}$ and $NO_2/NO_x$ concentrations in Curitiba are Praça Ouvidor Pardinho (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, PM2.5 and $NO_2$ ($\mu g/m^3$)

| | 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

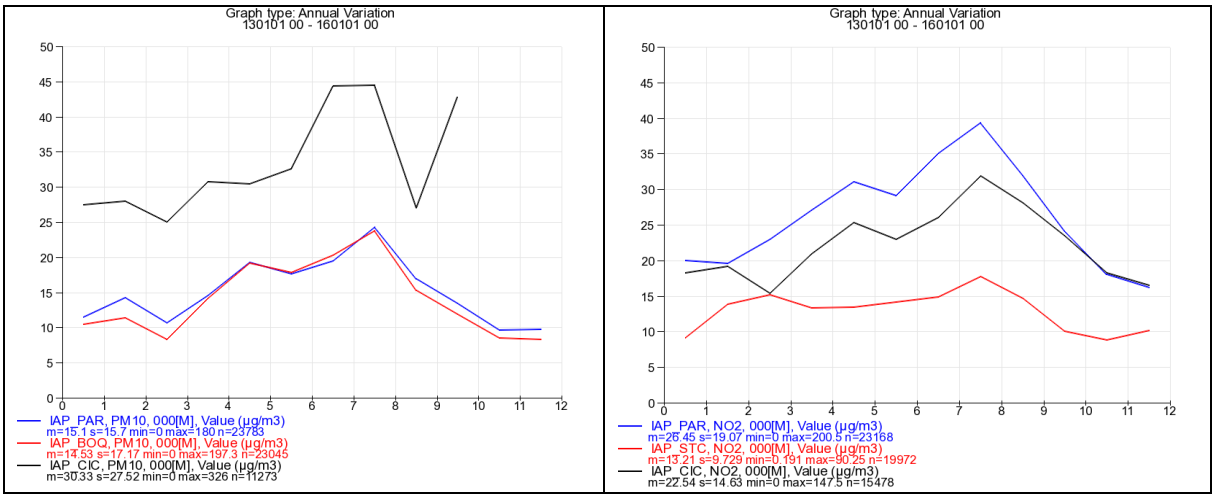



**Figure 4.2.1** Monthly average levels of $PM_{10}$ (left) and $NO_2$ (right) from the IAP network during the period 2013-2015. Note that there are large data gaps at station IAP_CIC, especially for $PM_{10}$.

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 $PM_{10}$ the levels are very similar between IAP_PAR and IAP_BOQ, which indicates that this pollutant is fairly homogeneous over the city. The $PM_{10}$ levels inside the city are well below the Brazilian standards and also below WHO guidelines. The $PM_{10}$ 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 $NO_2$ levels are found in the city center at IAP_PAR, which is situated close to a trafficked road. The $NO_2$ 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 $NO_2$ 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, $PM_{10}$, $NO_2$ and $NO_x$ show daily variations with one peak in the morning and a second one in the evening or night.

For $NO_2$ 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 $NO_2$ 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.

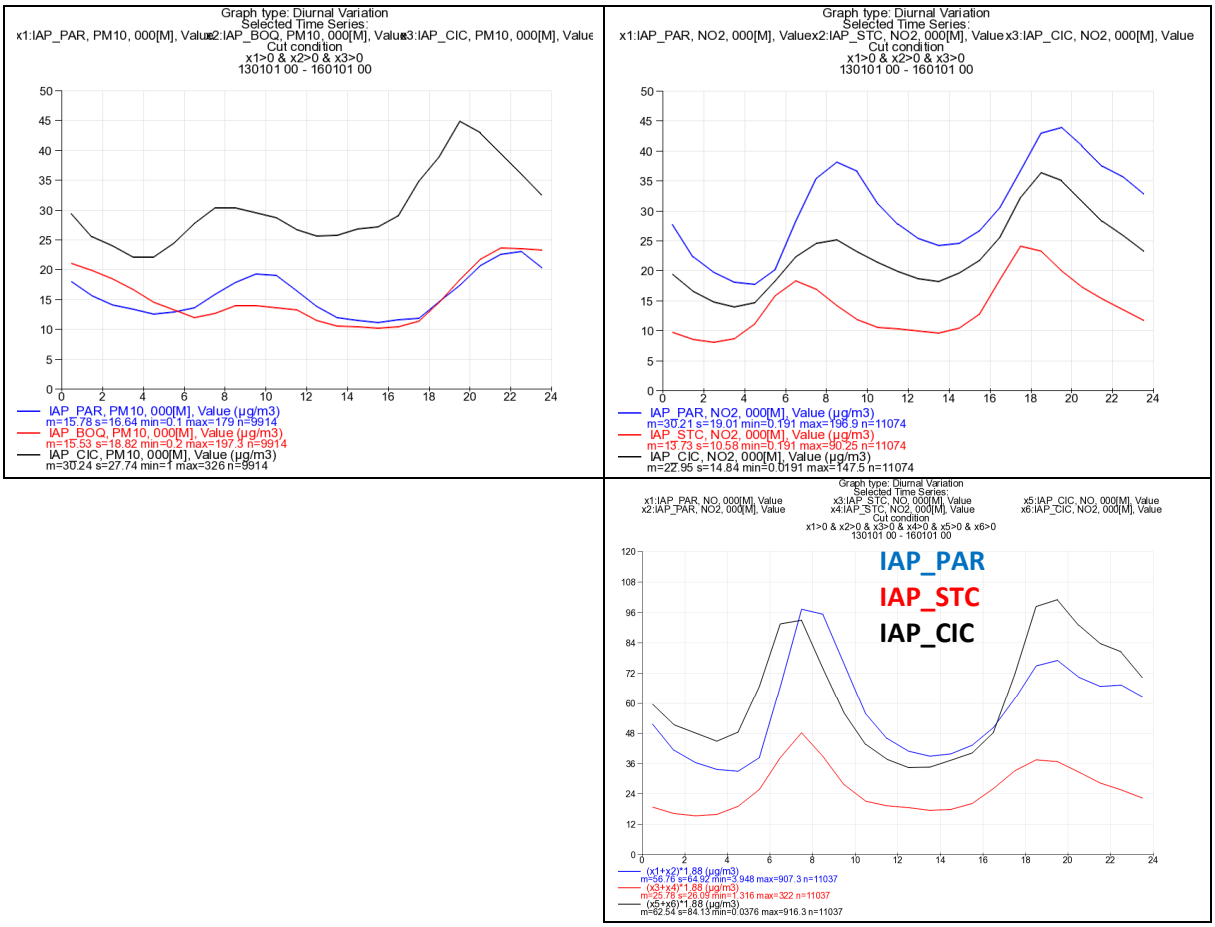



**Figure 4.2.2** Daily variation in $PM_{10}$ (top, left), $NO_2$ (top, right) and $NO_x$ (bottom, right) levels as registered in the IAP network during 2013-2015. To improve the comparison, only simultaneous valid data were included.

For $PM_{10}$ the long-range transported contribution is relatively higher than for $NO_2$ and $NO_x$, as indicated by the relatively smaller diurnal variations in comparison to mean levels. For IAP_CIC the daily variation of $PM_{10}$ is fairly similar to that for $NO_2$, so the dominating local source is likely traffic or an activity that has the same temporal variation as the traffic in this zone. The $PM_{10}$ 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/m$^3$)

| | **$PM_{10}$ 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, $PM_{10}$, $NO_2$ 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 $PM_{10}$ 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 PM2.5 mean level at this station was 10.3 µg/m$^3$, with maximum daily levels rising to 35-40 µg/m$^3$. BC levels measured with the aethalometer averaged to 2.2 µg/m$^3$, with maximum daily values of 8 µg/m$^3$ during traffic peak hours. Also brown carbon was registered, but with a much lower average levels <0.2 µg/m$^3$ and with less pronounced daily variation.

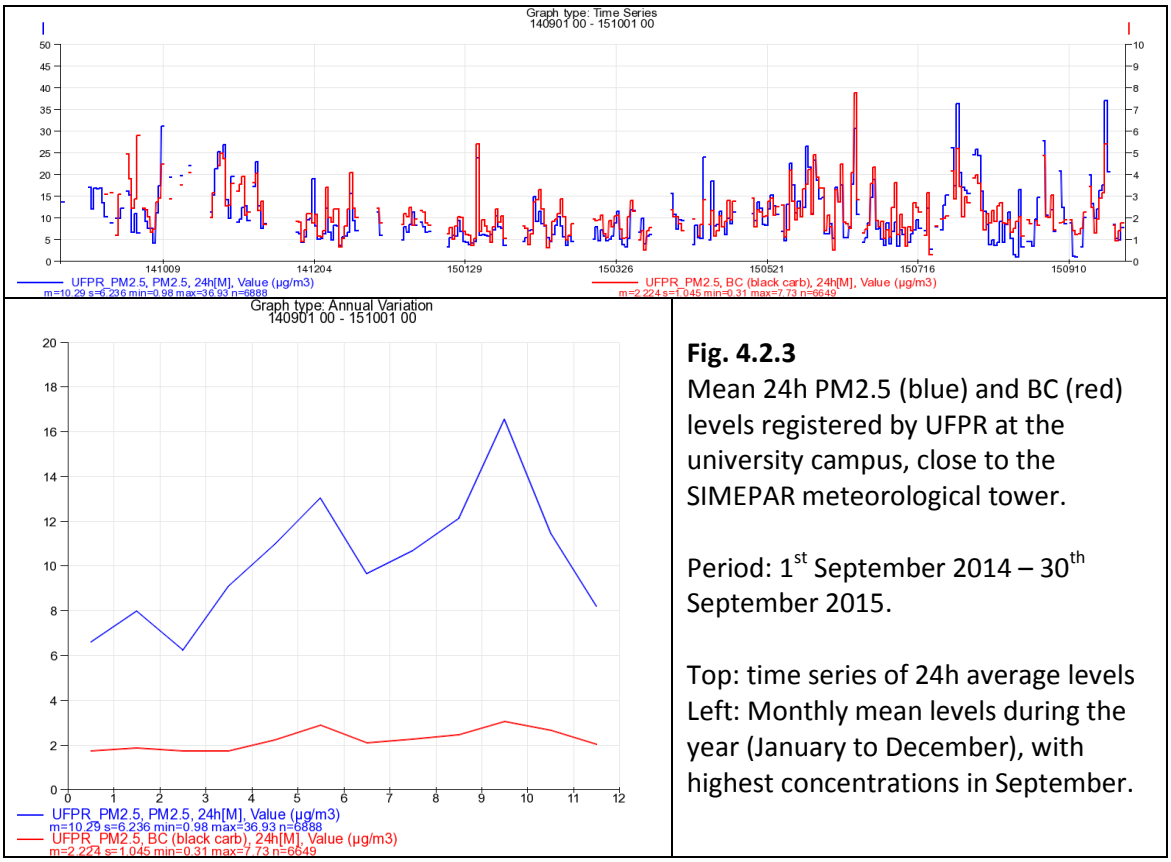



**Fig. 4.2.3**
Mean 24h PM2.5 (blue) and BC (red) levels registered by UFPR at the university campus, close to the SIMEPAR meteorological tower.

Period: 1st September 2014 – 30th September 2015.

Top: time series of 24h average levels
Left: Monthly mean levels during the year (January to December), with highest concentrations in September.

### 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 µg/m$^3$ at the roof and 5.5 µg/m$^3$ at street level, leaving a contribution of 3.2 µg/m$^3$ from the local traffic down on the street.

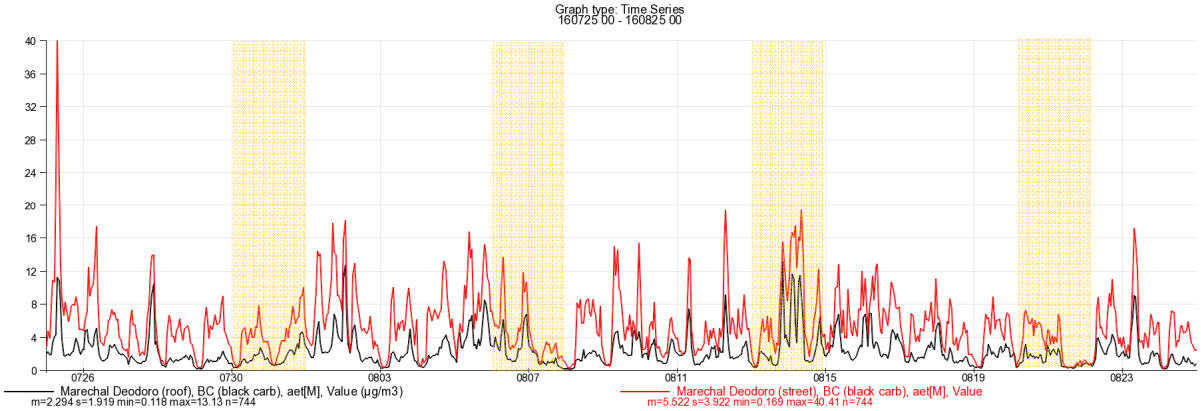



**Figure 4.2.4** Hourly data of BC at Marechal Deodoro station, at roof level (black) and at street level (red). Unit: µg/m$^3$. Weekends marked in pink.

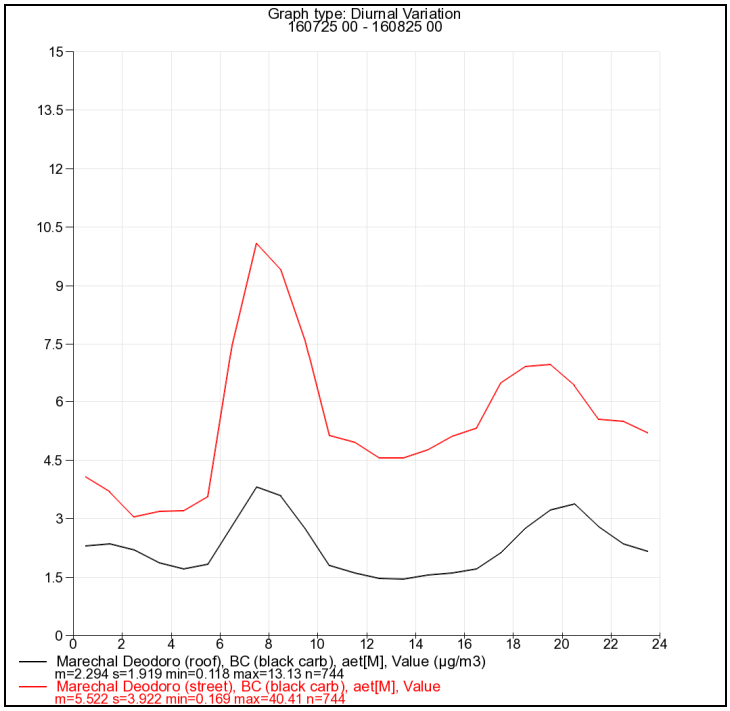



**Figure 4.2.5** Daily variation of BC levels at Marechal Deodoro station, at roof level (black) and at streeg level (red).
Unit: µg/m$^3$.

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** ($\mu g/m^3$) | **street level** ($\mu g/m^3$) | **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 $PM_{2.5}$ monitoring, there were technical problems with the street level monitor. However, the mobile monitoring performed with bikes offers simultaneous data of both BC and $PM_{2.5}$ 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 $PM_{2.5}$ time series. Assuming this relation between BC and $PM_{2.5}$ within the Marechal Deodoro street canyon, the $PM_{2.5}$ concentration was estimated as approximately 17 $\mu g/m^3$ at street level due to the impact of local traffic (Fig. 4.2.6). At roof level, the mean $PM_{2.5}$ concentration was 7 $\mu g/m^3$ during the monitoring campaign.

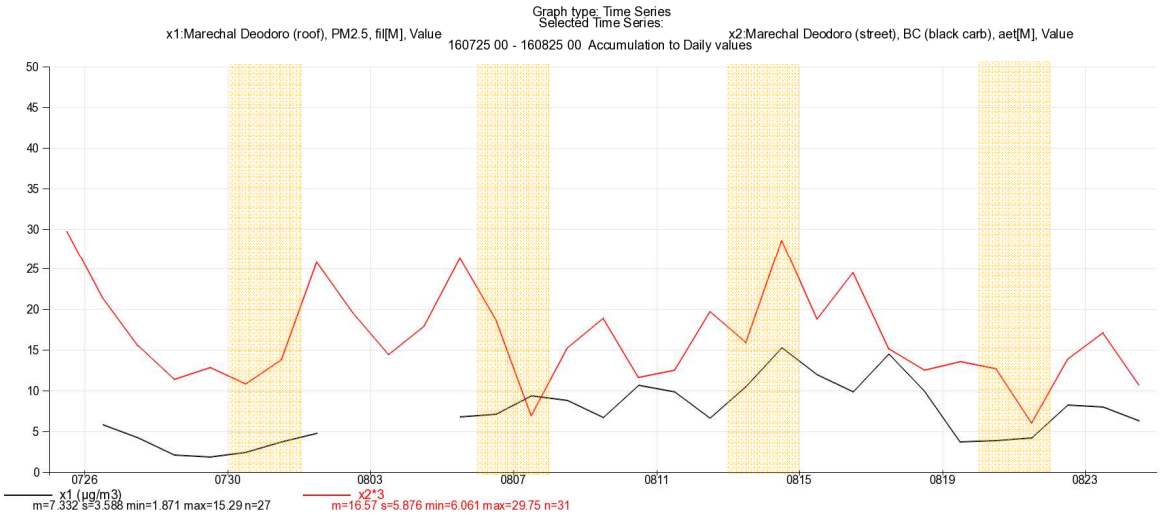



**Figure 4.2.6** Daily $PM_{2.5}$ data at Marechal Deodoro station, at roof level (black) and at street level (red). Note that the street level $PM_{2.5}$ data has been reconstructed from the hourly BC data, applying a scale factor of 3 (factor taken from the simultaneous $PM_{2.5}$ and BC registered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

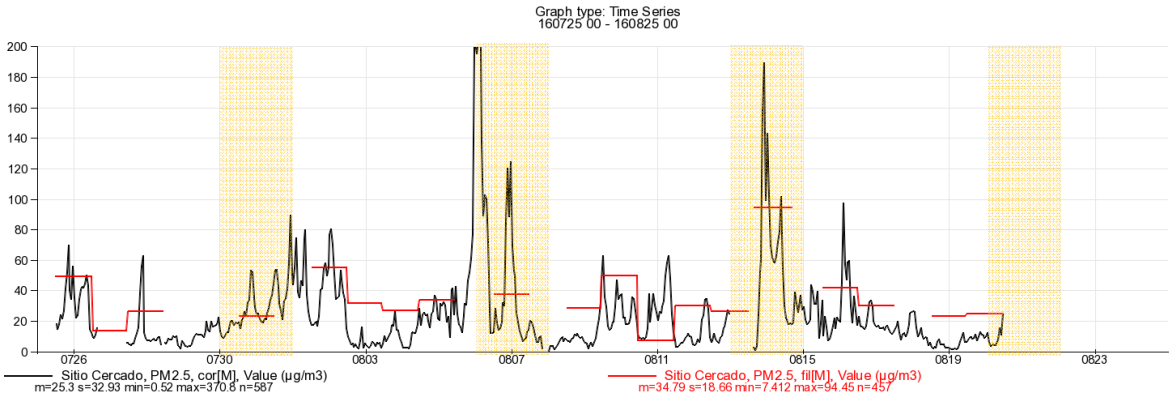



**Figure 4.2.7** Daily $PM_{2.5}$ (red, filter sampling) and hourly $PM_{2.5}$ (black, Dusttrak) from Sítio Cercado station. Unit: µg/m$^3$. Weekends marked in pink.

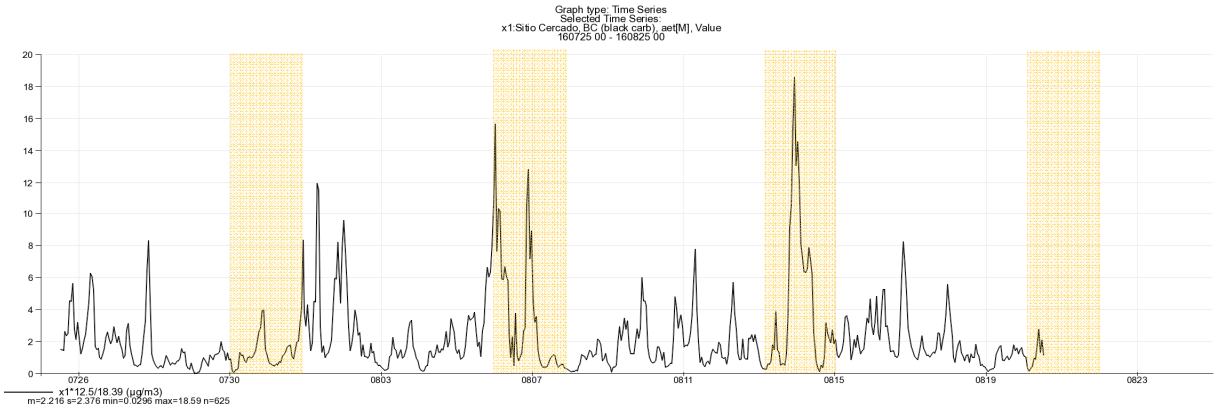



**Figure 4.2.8** Daily BC (measured by the micro aethalometer) from Sítio Cercado station, after correction against EC analysis of filter samples (NIOSH protocol). Unit: µg/m$^3$. Weekends marked in pink.

**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.

| | PM2.5 | EC | OC | Non-C |
|---|---|---|---|---|
| Average 17 daily samples (µg/m$^3$) | 36.2 | 2.6 | 11.2 | 22.4 |
| Percentage of PM2.5 | 100% | 7.1% | 31.1% | 61.8% |

While BC mean levels in this residential area are very similar – in average about 2 µg/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 Sapiranga, 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 $\mu g/m^3$, with some hotspots where concentrations surpassed 12.0 $\mu g/m^3$. 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 $\mu g/m^3$ and $PM_{2.5}$ above 28.0 $\mu g/m^3$ 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 $\mu g/m^3$, and hotspots with concentrations above 28.0 $\mu g/m^3$. 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.

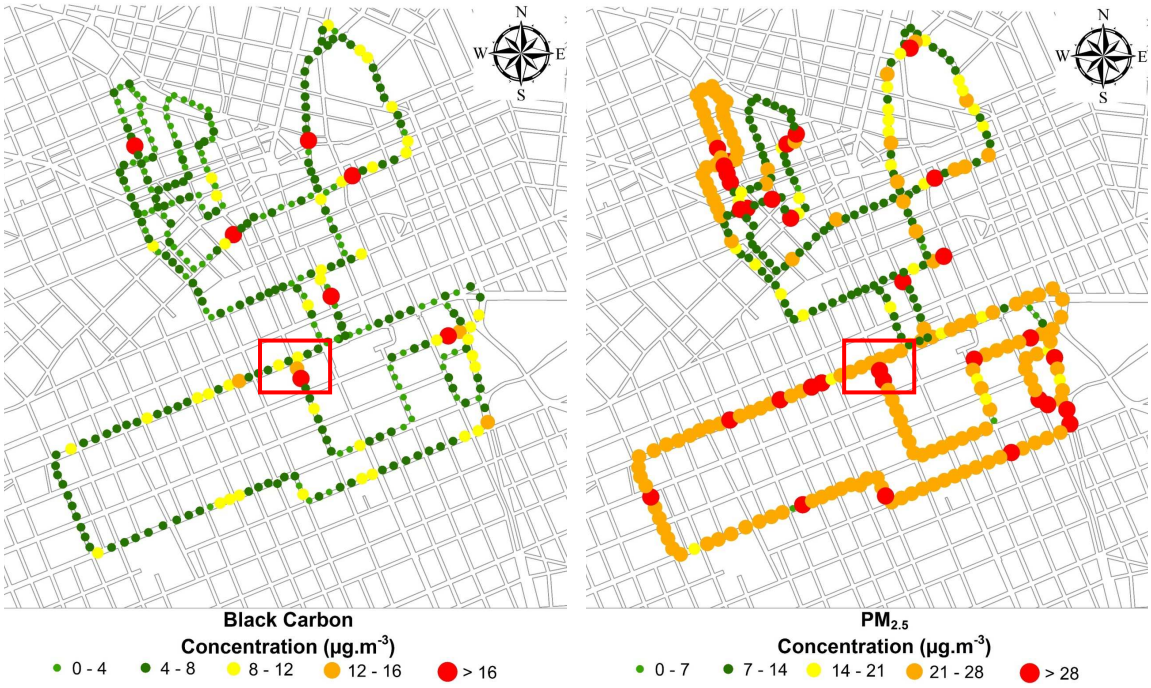



**Figure 4.2.9** Spatial distribution of aggregated median BC concentrations (left) and $PM_{2.5}$ (right) using three morning runs.

### Measurements of $NO/NO_2$ 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 $NO_2$ concentration measured by chemiluminescence monitor and Ogawa samplers. The sampling period started on June 27$^{th}$ at the ground level and on June 30$^{th}$ 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 29$^{th}$ of July to the 12$^{th}$ of August and from the 15$^{th}$ to the 29$^{th}$ of August 2016 at all the 11 locations where the Ogawa samplers were installed.

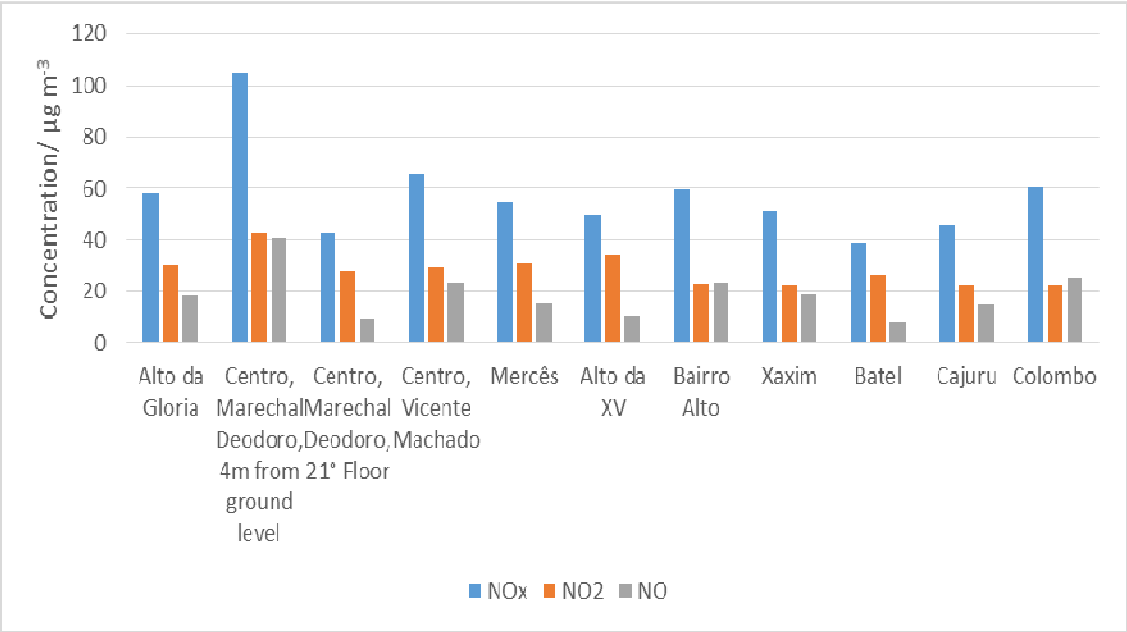



**Figure 4.2.10** NO, $NO_2$ and $NO_x$ concentrations between 29th July and 12th August, 2016.

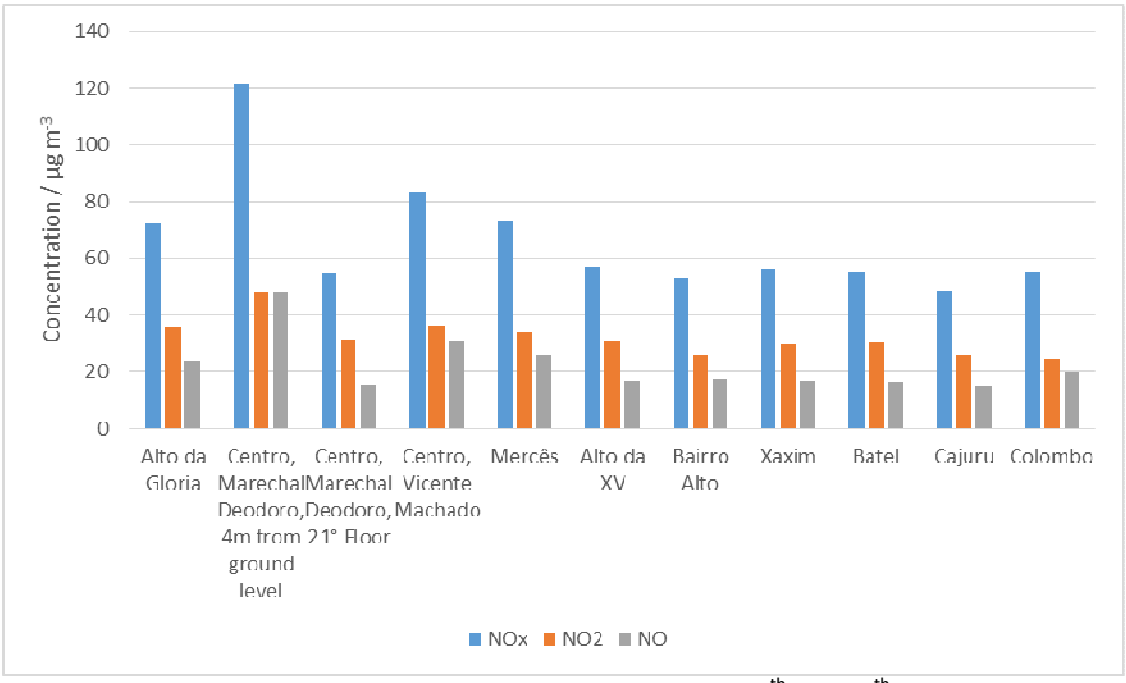



**Figure 4.2.11** NO, $NO_2$ and $NO_X$ concentrations between 15th and 29th August, 2016.

As shown in the Figures 4.2.10-11, the concentration profiles of NO and $NO_2$ 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).

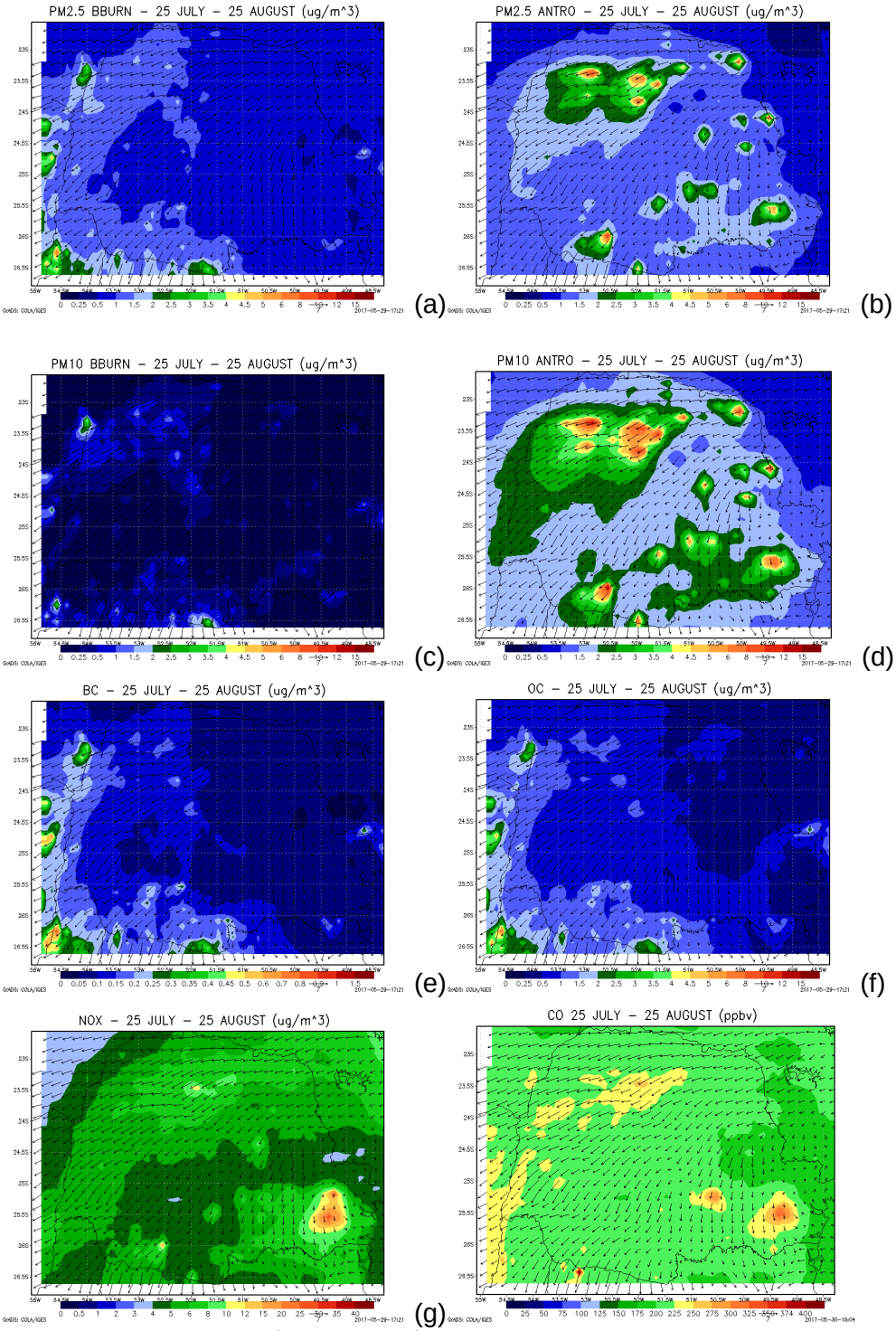
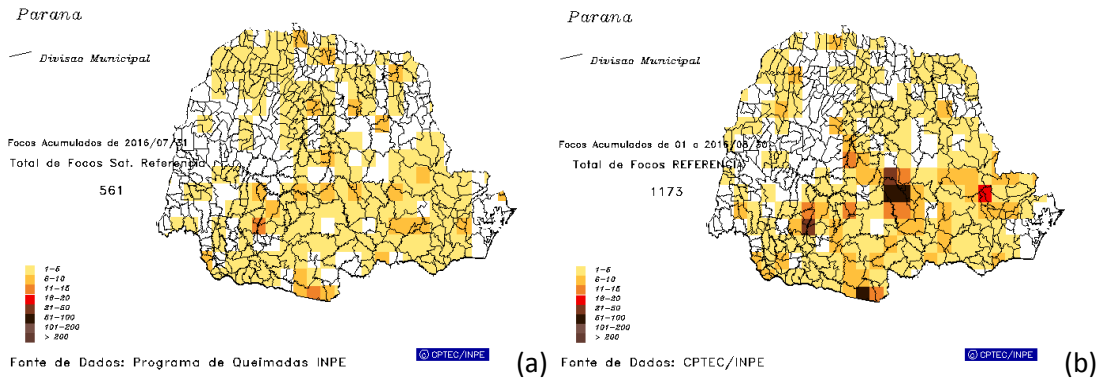



**Figure 4.3.1** For the period 25th July to 25th August average $PM_{2.5}$ from biomass burning (a) and anthropogenic sources [µg/m$^3$] (b), $PM_{10}$ from biomass burning (c) and anthropogenic sources [µg/m$^3$] (d), BC [µg/m$^3$] (e), OC [µg/m$^3$] (f), $NO_x$ [ppbv] (g) and CO [ppbv] (h).

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).



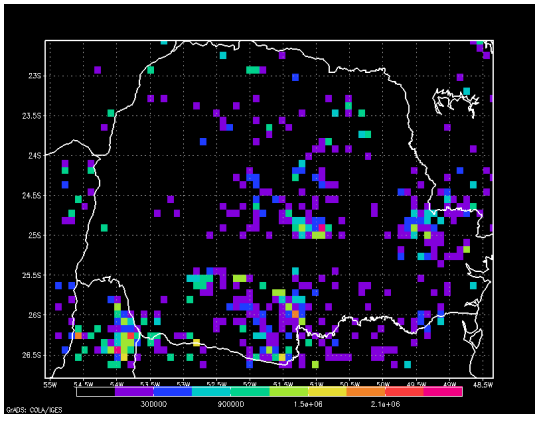




**Figure 4.3.2** Hotspots in July (a) and August (b); and fire size PREP-CHEM-SRC output for 25 July to 25 August (c) registered by satellite data. Source: DSA/INPE

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.

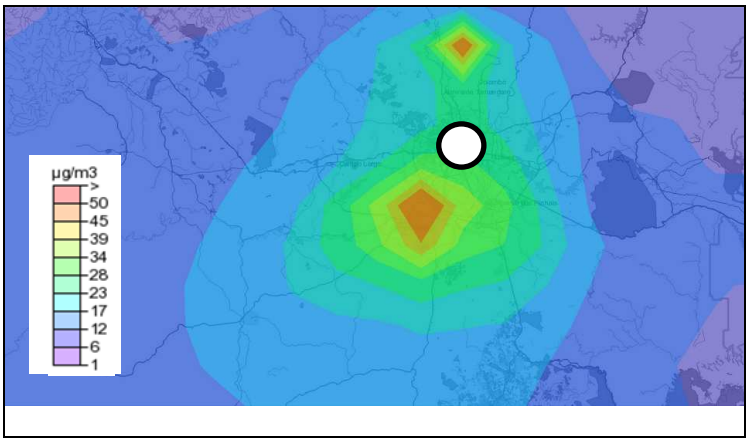



**Figure 4.3.3** Simulated $NO_x$ levels over the eastern part of the Paraná state for the period 20th July – 28th August, using IAP emission inventory. Emissions within the Curitiba municipality are excluded. Curitiba city center marked with white circle. Unit: µg/m$^3$.

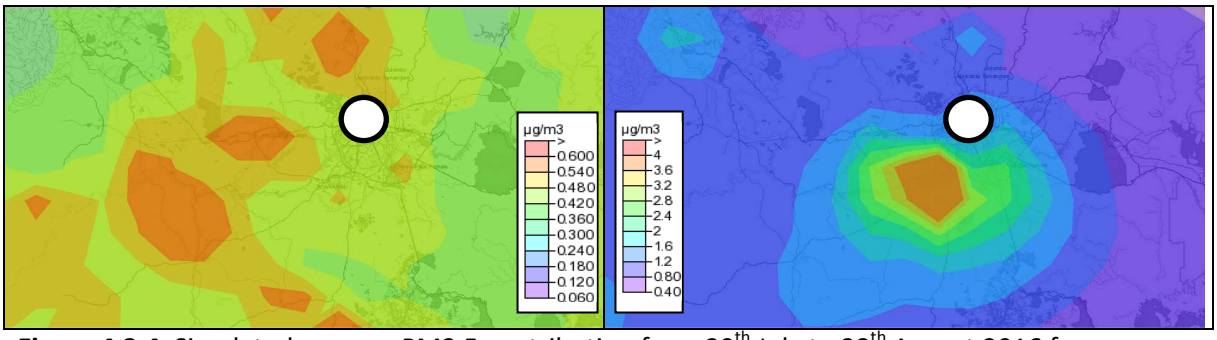



**Figure 4.3.4** Simulated average PM2.5 contribution from 20th July to 28th August 2016 from biomass burning (left) and anthropogenic emissions (IAP inventory excluding sources within the Curitiba municipality, right). Curitiba city center marked with a white circle.

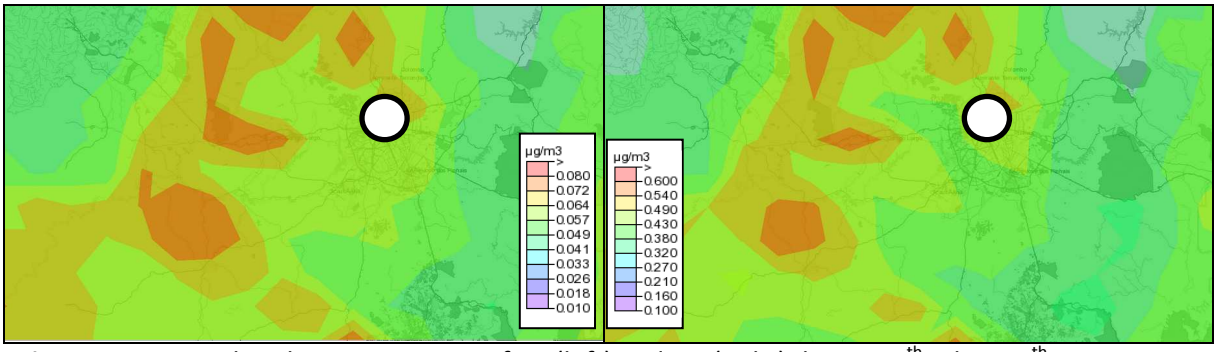



**Figure 4.3.5** Simulated concentrations of BC (left) and OC (right) during 20th July – 28th August 2016 from the summed contributions of anthropogenic (EDGAR) and biomass burning (3BEM). Curitiba city center marked with a white circle.

## 4.4 Local dispersion modeling and integrated analysis

### Simulated $NO_x$, BC and $PM_{2.5}$ 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).

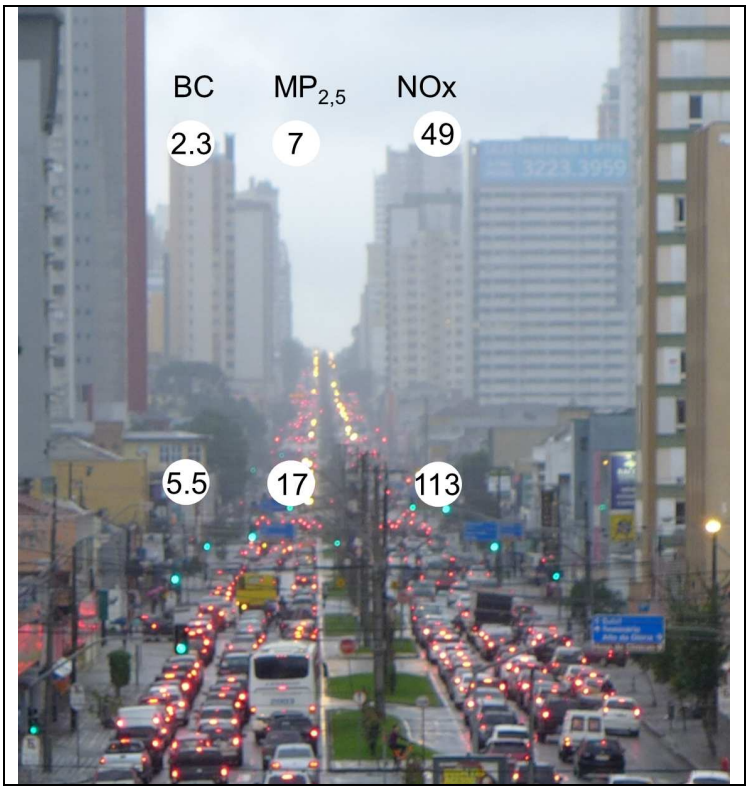



**Figure 4.4.1** Monitored mean concentrations at Marechal Deodoro roof level and street level during the monitoring campaign 25th July – 25th August 2016. Unit: µg/m3.
*Note: Photo shows another street in Curitiba, used just for illustrating a typical street canyon.*

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 $PM_{2.5}$.

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.

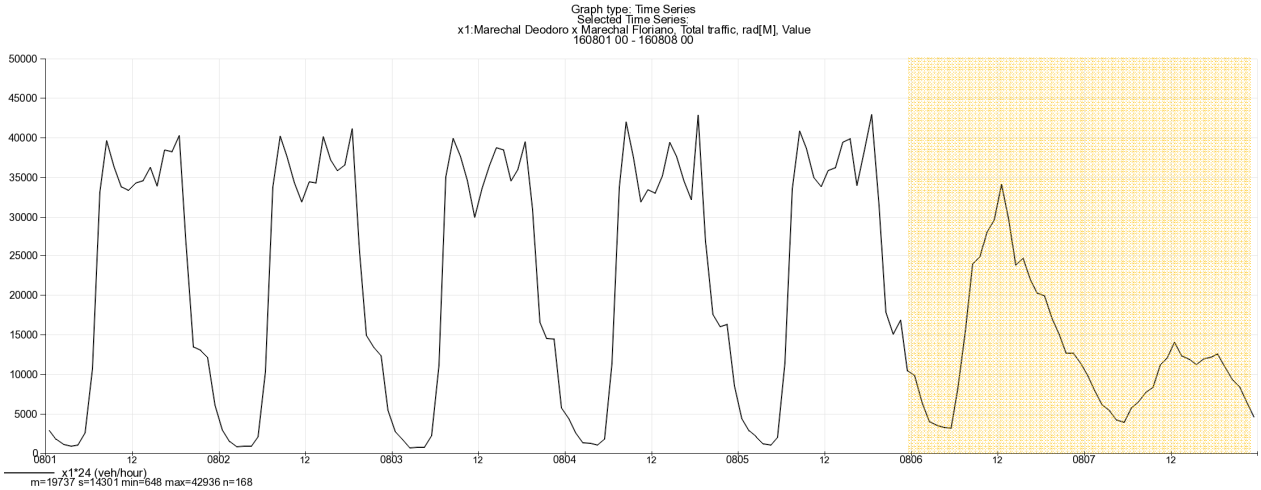



**Fig. 4.4.2** Hourly traffic volume along Marechal Deodoro during one of the weeks of the monitoring, as registered by the speed trap/radar located on Marechal Deodoro street, close to the monitoring station. Weekend days marked in pink.

***$NO_x$ 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 µg/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 µg/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.

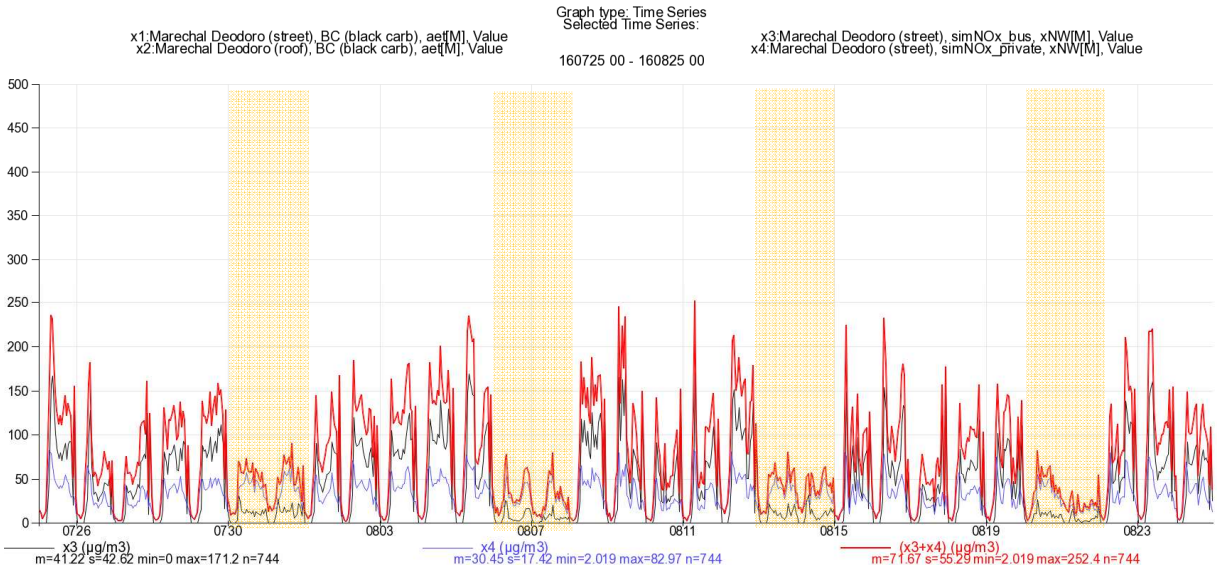



**Fig. 4.4.3** Simulated $NO_x$ levels at Marechal Deodoro: buses (black), private vehicles (blue) and the sum of both (red).

**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$^3$)** | | |
|---|---|---|---|---|---|---|
| ***Period*** | ***street*** | ***roof*** | ***increment*** | ***public transport*** | ***private traffic*** | ***summed*** |
| 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).

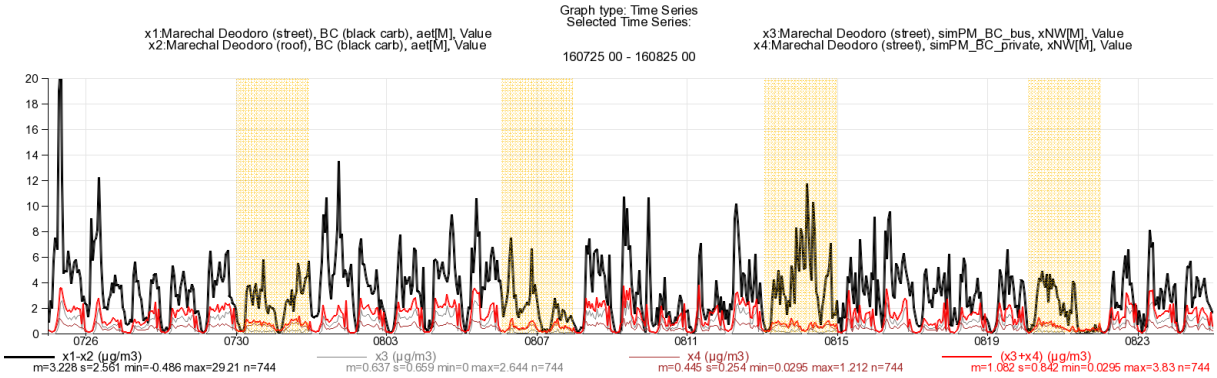



**Fig. 4.4.4** Hourly data of locally generated black carbon (BC) from measurements (street minus roof concentrations, in black), simulated impact from buses (thin grey), from private vehicles (thin brown) and total simulated contribution from the street (red). Unit: µg/m$^3$. Weekends are indicated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

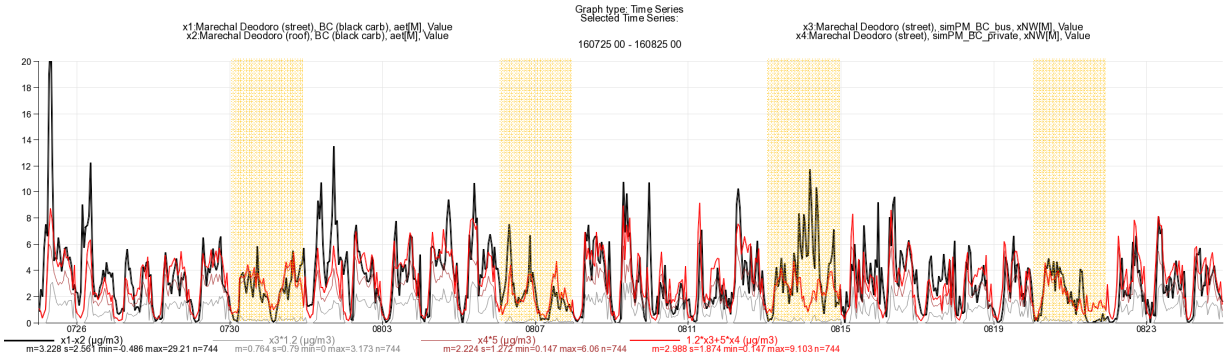
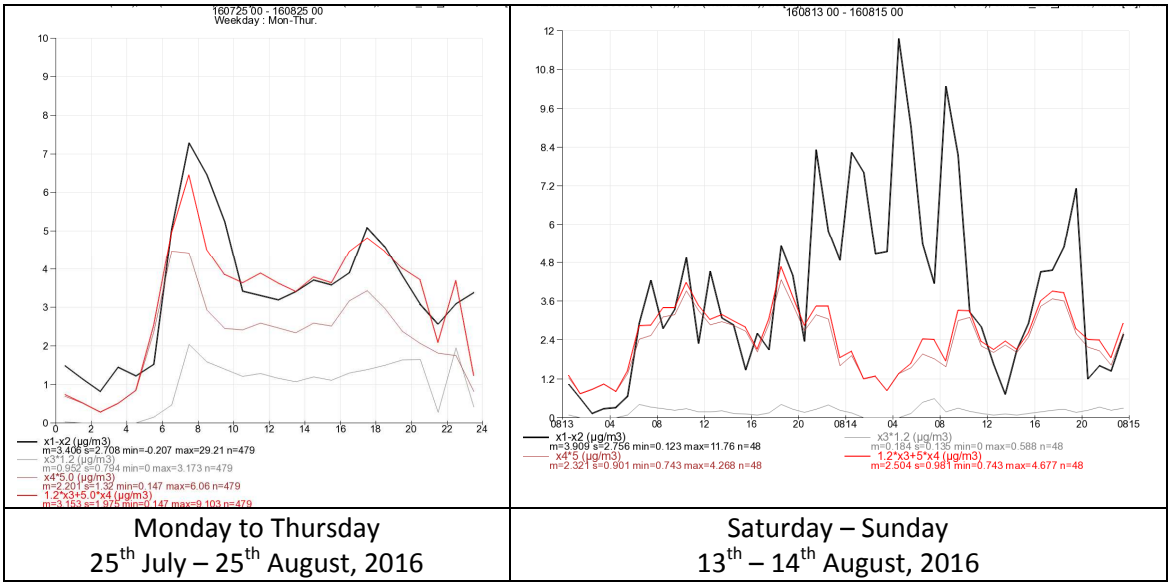



**Fig. 4.4.5** Hourly data of locally generated black carbon (BC) from measurements (street minus roof concentrations, in black), and simulated – after multiple regression - impact from buses (thin grey), from private vehicles (thin brown) and total simulated contribution from the street (red). Unit: µg/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: µg/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.




| Monday to Thursday<br>25th July – 25th August, 2016 | Saturday – Sunday<br>13th – 14th August, 2016 |
|---|---|

**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/m$^3$). Table 4.4.3 summarizes the comparison.

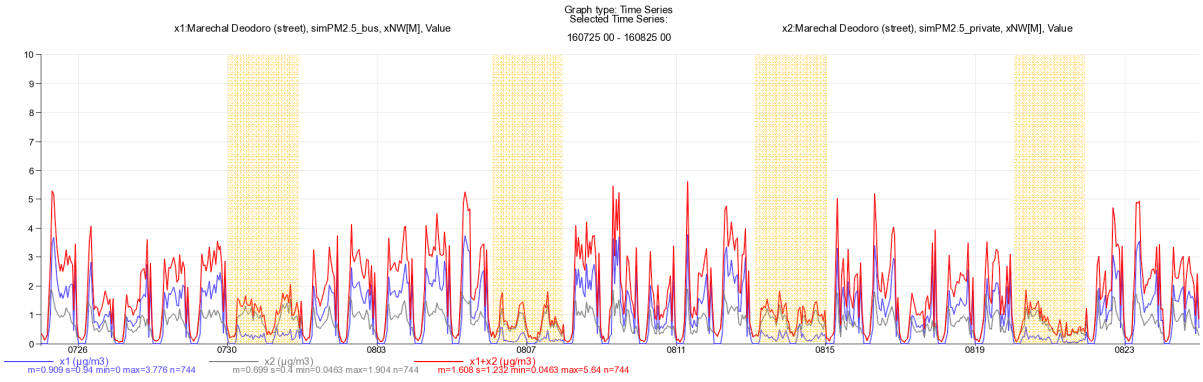



**Fig. 4.4.7** Hourly simulated data of locally generated $PM_{2.5}$ impact from buses (grey), private vehicles (blue) and summed traffic contribution (red). Units: µg/m$^3$.

**Table 4.4.3** Monitored and simulated PM2.5 levels at Marechal Deodoro.

| **Unit: µg/m$^3$** | **monitored BC** | | | **simulated BC (street)** | | |
|---|---|---|---|---|---|---|
| | ***street*** | ***roof*** | ***increment*** | ***public transport*** | ***private traffic*** | ***summed*** |
| 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/m$^3$) with the monitored increment (9.3 µg/m$^3$), 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 $NO_2/NO_x$ 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/m$^3$. 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 |

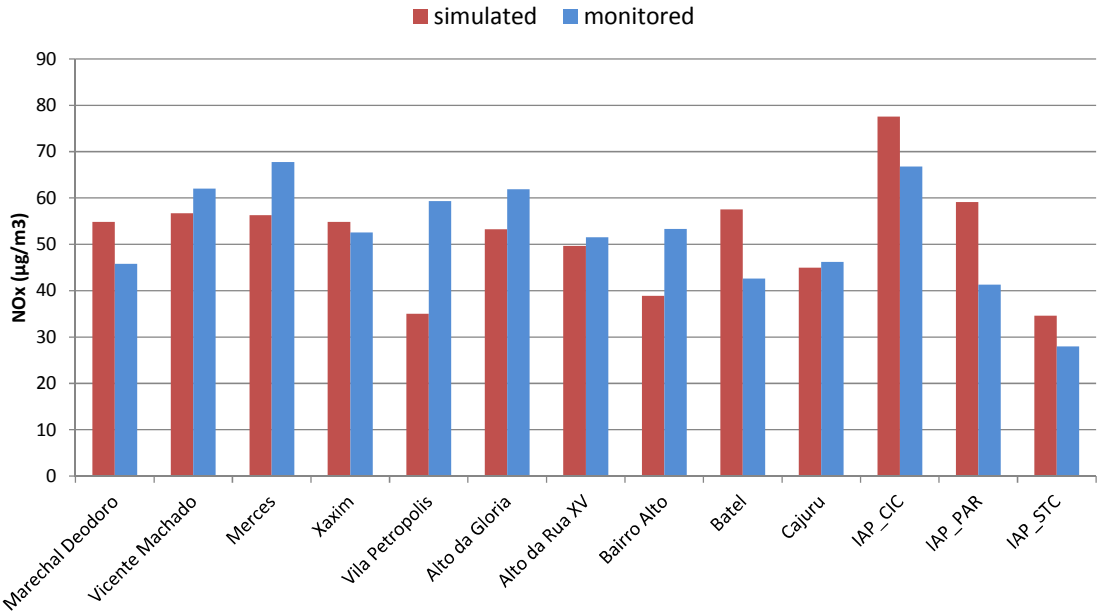



**Figure 4.4.8** Comparison between simulated $NO_x$ urban background levels (red) and monitor data (blue) for the period July 29th to August 29th 2016. The IAP data are taken from the IAP monitoring network, the others measured with passive samplers.

The overall result, as illustrated in Fig. 4.4.8, is fairly good in terms of average concentration leves, simulated data has an average of 51.8 µg/m$^3$ and the measured 52.2 µg/m$^3$. However, the spatial correlation is 0.43, i.e. there are larger differences between simulated and observed NOx 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 $km^2$) 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 NOx 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.

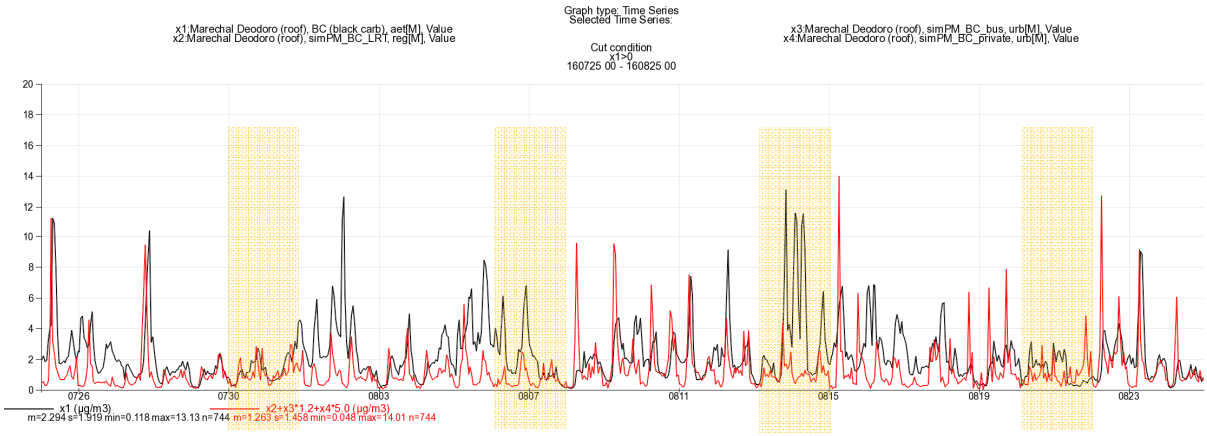



**Fig. 4.4.9** Monitored and simulated BC levels at Marechal Deodoro roof level: Monitored (black), simulated (red) consisting of regional model contribution plus local impact of buses and private vehicles. The local contribution has been modified according to the regression results from the street canyon 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 | *This contribution is likely underestimated due to lack of regional emission inventories for BC* |
| Public transport (buses) | 0.13 | |
| Private traffic | 1.07 | |
| ***Summed:*** | ***1.27*** | |
| | | |
| ***Monitored:*** | ***2.29*** | |
| Unknown sources: | 1.02 | *Except for the underestimated LRT, there may also be a contribution from residential combustion within the city (not included in the model simulation).* |

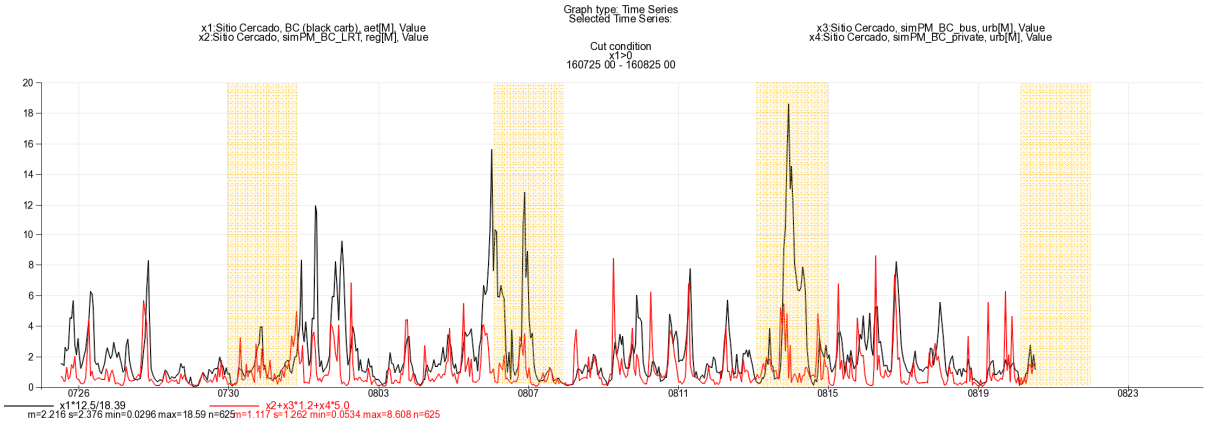



**Fig. 4.4.10** Monitored and simulated BC levels at Sitio Cercado: Monitored (black), simulated (red) consisting of regional model contribution plus local impact of buses and private vehicles. The local contribution has been modified according to the regression results from the street canyon Marechal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

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

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

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 14$^{th}$ 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.

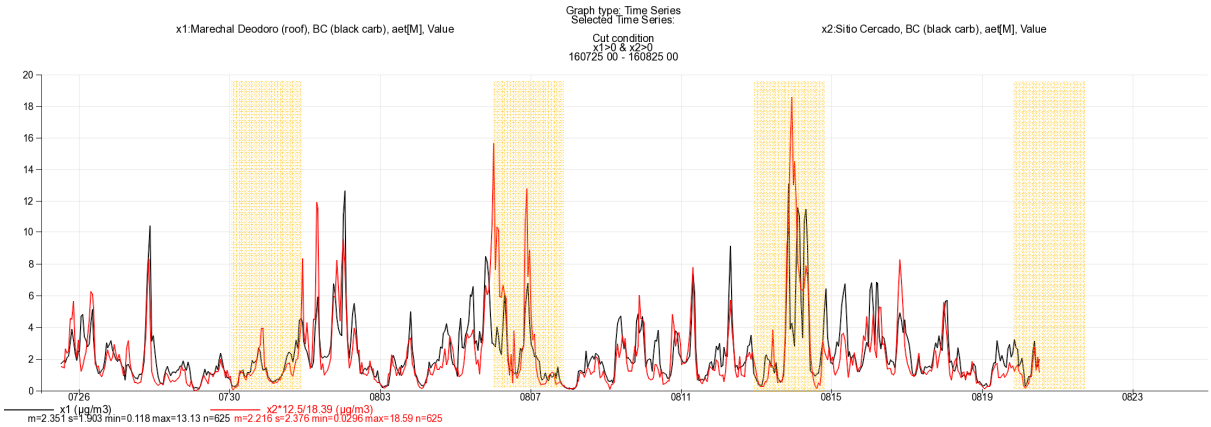



**Fig. 4.4.11** Monitored and simulated BC levels at Marechal Cercado roof level (black) and Sitio Cercado (red).

In summary, the comparison of BC levels at the two stations indicates rather uniform urban background levels of about 2 µg/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 µg/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 ***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 $PM_{2.5}$ 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 $PM_{2.5}$ impact in this area. The historical $PM_{2.5}$ data set from the UFPR campus (Fig. 4.2.3), with mean levels of 10 µg/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.

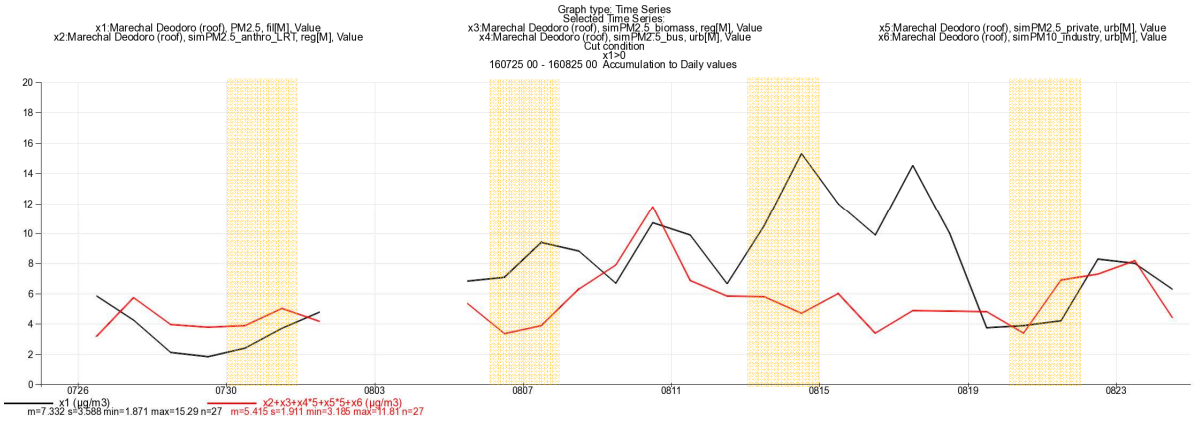



**Fig. 4.4.12** Monitored and simulated daily $PM_{2.5}$ levels at Marechal Deodoro roof level: Monitored (black), simulated (red) consisting of regional model contributions from anthropogenic and biomass burning plus local impact of buses, private vehicles and industry within the Curitiba municipality. 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** ($\mu g/m^3$) | comment |
|---|---|---|
| Long-range transport (LRT) from regional model:<br>- anthropogenic<br>- biomass burning | <br><br>1.8<br>0.5 | *Assumed $PM_{2.5}/PM_{10}$ ratio 0.7 for IAP industrial emissions. LRT includes IAP emissions outside the Curitiba municipality.* |
| 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 | |

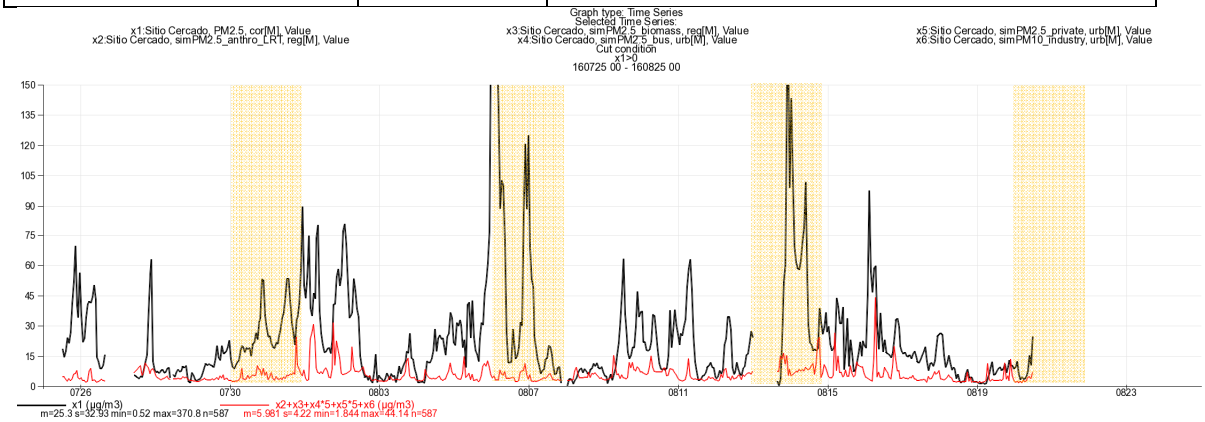



**Fig. 4.4.13** Monitored and simulated daily $PM_{2.5}$ levels at the residential station Sitio Cercado: monitored (black), simulated (red) consisting of regional model contributions from anthropogenic and biomass burning plus local impact of buses, private vehicles and industry within the Curitiba 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** ($\mu g/m^3$) | comment |
|---|---|---|
| Long-range transport (LRT) from regional model:<br>- anthropogenic<br>- biomass burning | <br><br>3.4<br>0.5 | *Assumed $PM_{2.5}/PM_{10}$ ratio 0.7 for IAP industrial emissions. LRT includes IAP emissions outside the Curitiba municipality.* |
| Public transport (buses) | 0.4 | |
| Private traffic | 1.4 | |
| ndustry inside Curitiba municipality | 0.6 | |
| ***Summed:*** | ***6.3*** | |
| | | |
| ***Monitored:*** | ***25.3*** | |
| Unknown sources: | 19.0 | *Many unidentified sources to $PM_{2.5}$ in this area* |

**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.

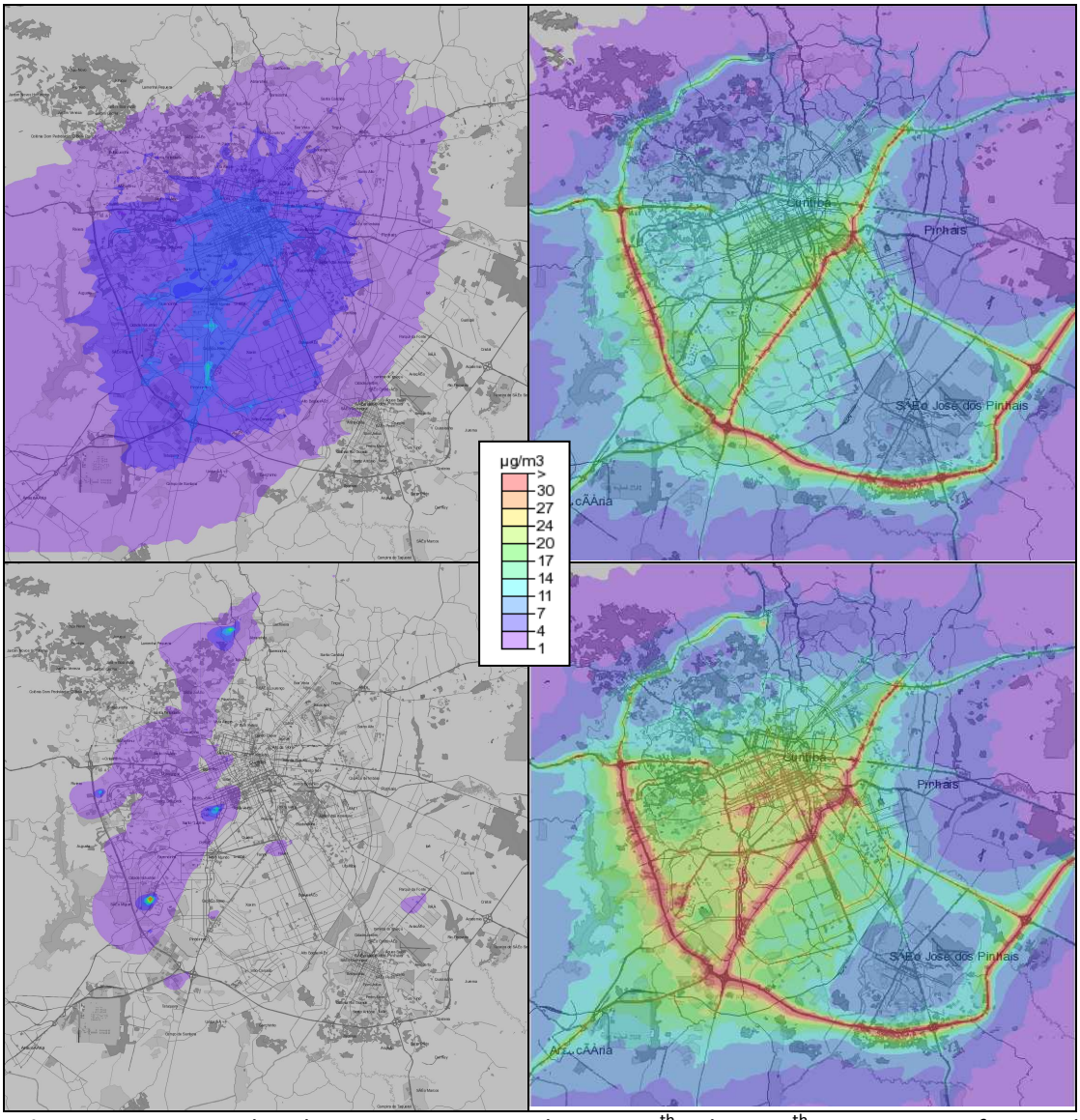



**Figure 4.4.14** Simulated average $NO_x$ contribution 25th July – 24th August 2016 from public transport (upper left), private traffic (upper right), local industries (bottom left) and summed local impact.

The local contributions to ***NOx*** (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 NOx. In smaller areas around the industrial sources, there is a dominating impact from those industrial emissions.

Local NOx 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

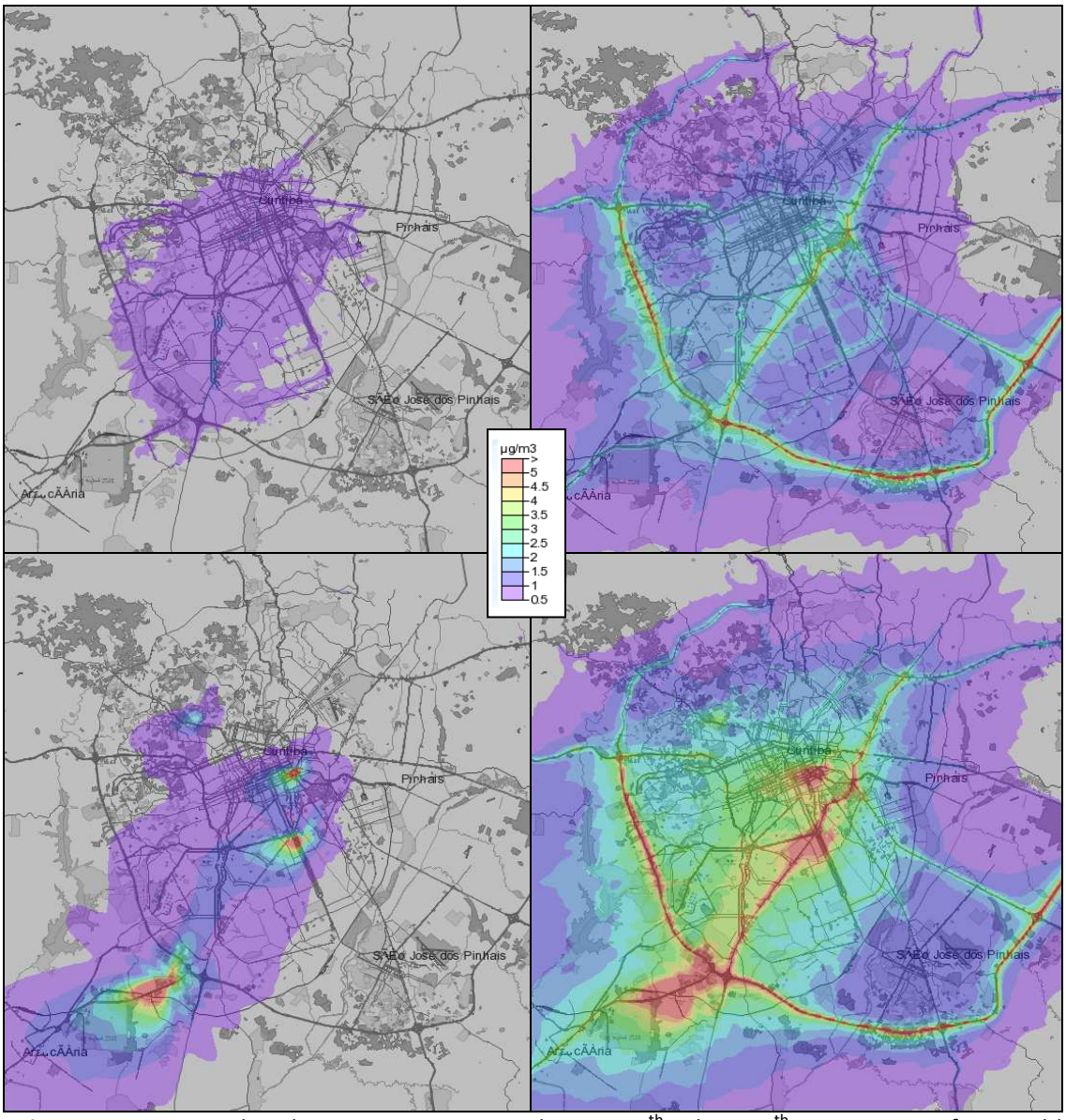



**Figure 4.4.15** Simulated average $PM_{2.5}$ contribution 25th July – 24th August 2016 from public transport (upper left), private traffic (upper right), local industries (PM2.5 emissions assumed 70% of PM10 emissions, bottom left) and summed local impact (bottom right).

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 PM2.5/PM10 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

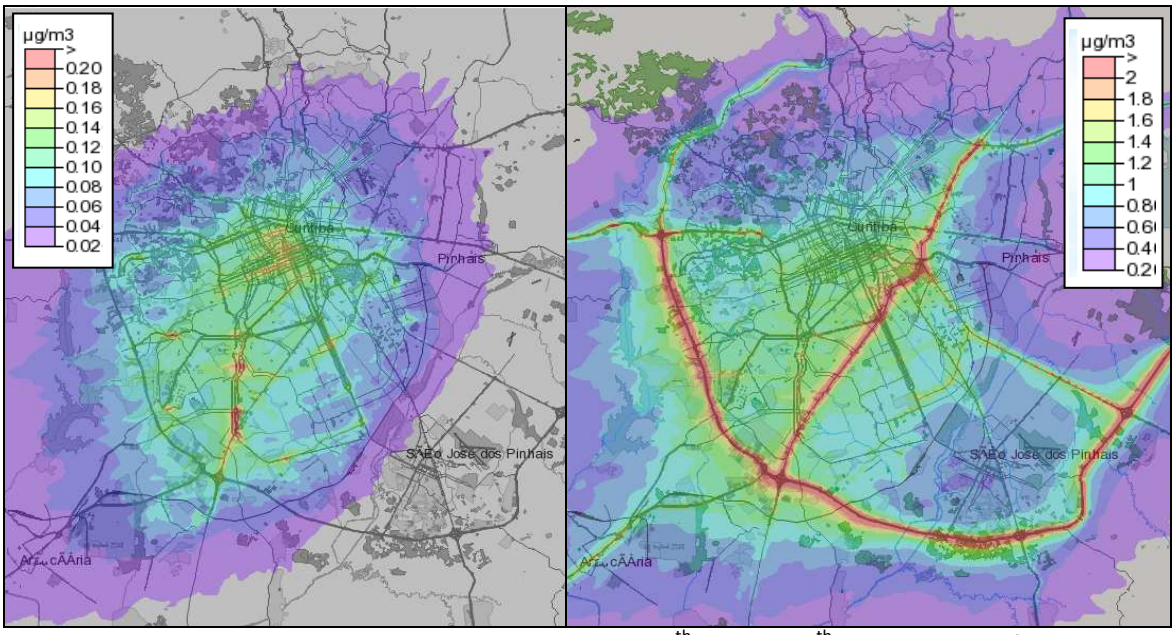



**Figure 4.4.16** Simulated average BC contribution 25th July – 24th August 2016 from public transport (upper left) and private traffic (upper right). Note color different scales! Bus emissions corrected with factor 1.2 and private traffic with factor 5.0, according to comparison with measurements in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

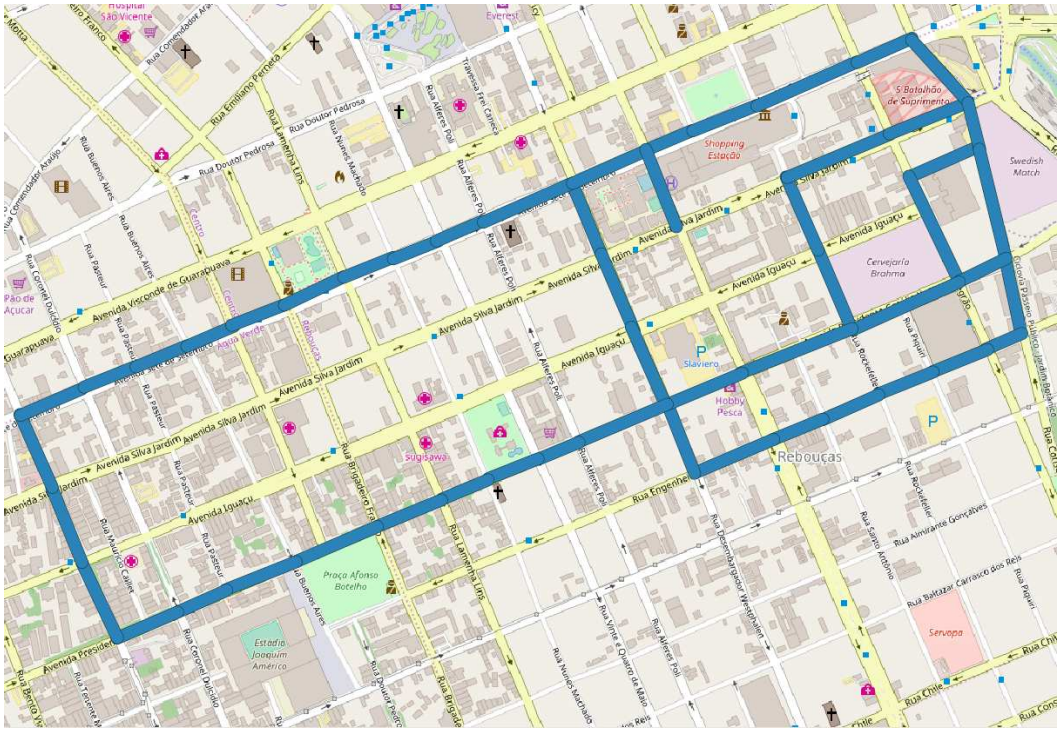



**Figure 4.4.17** The S1 route as it was simulated (the biking route was a bit more extended).

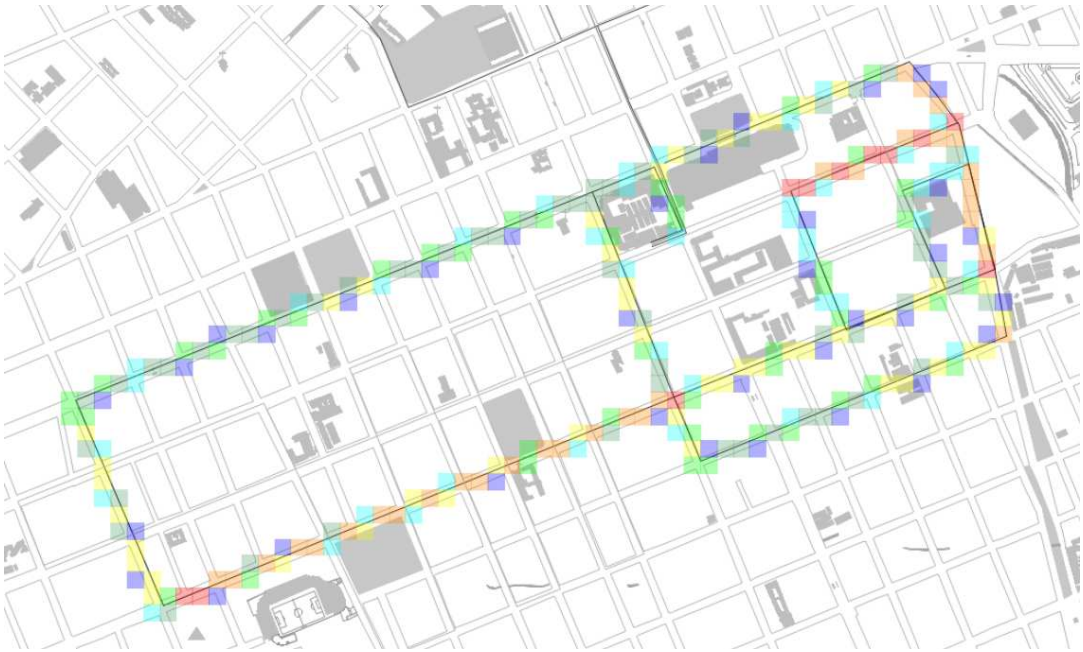


**Figure 4.4.18** Traffic volumes on a relative scale, where red color indicate volumes > 31000 veh/day. Maximum traffic intensity is found on Silva Jardim with 39000 veh/day. Public transport (buses) are found on all streets, except Tv. Pinheiro and Engenheiros Rebouças, according to the inventory.

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 Getulio 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.

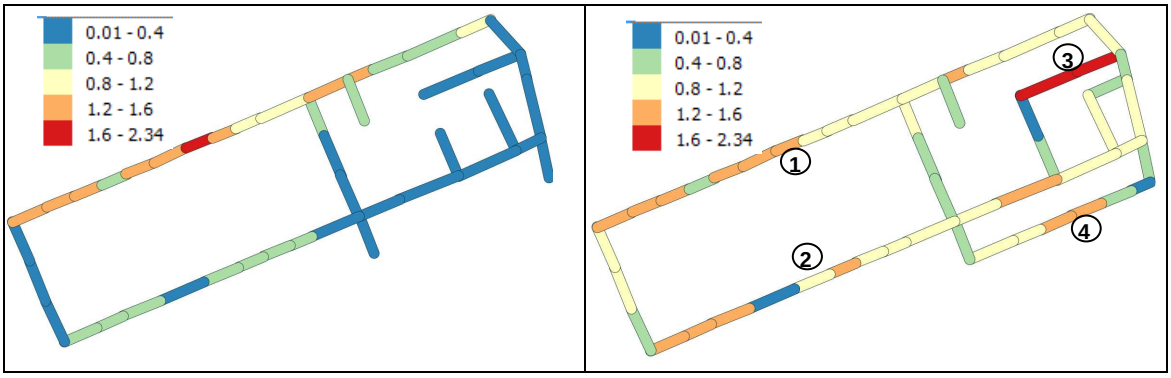



**Figure 4.4.19** Local contributions of BC from buses (left) and private traffic (right) on Wednesday morning August 03, between 08 and 10 hours. All levels corrected according to the comparison at the fixed Marechal Deodoro station. There are some streets along S1 route without buses, those streets 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.

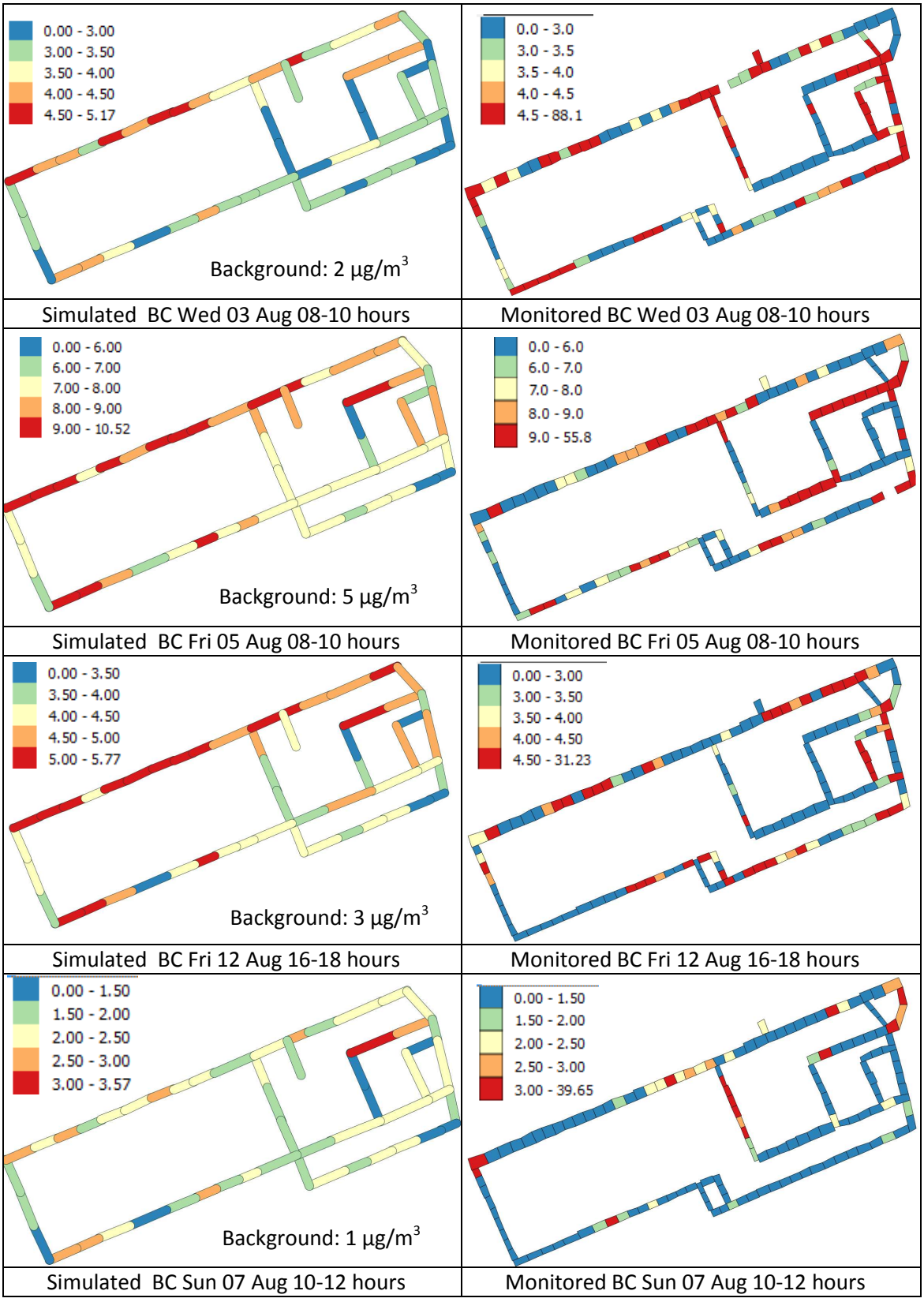



**Figure 4.4.20** Local contributions of BC from buses (left) and private traffic (right) for selected days and hours. All levels corrected according to the comparison at the fixed Marechal Deodoro station. Background concentrations taken from Marechal Deodoro roof station.

## 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 ***$PM_{10}$ daily mean*** values is illustrated in Fig. 4.5.2.

| unit: µg/m³ | $PM_{10}$ 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 ? |

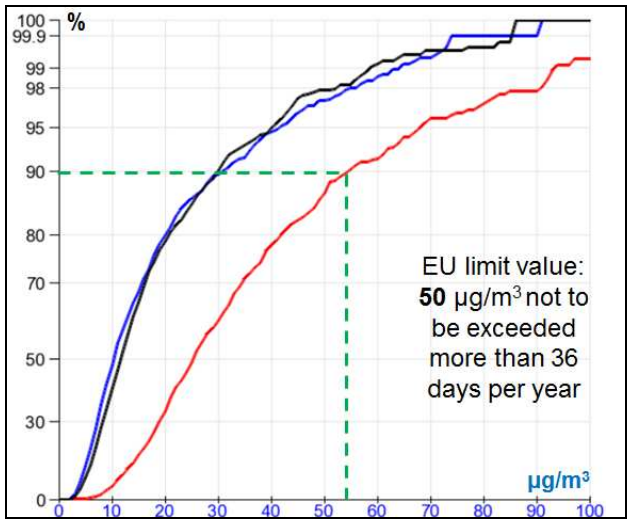
*expressed as 90th percentile

**Figure 4.5.1** Overview of limit values and recommendations for $PM_{10}$, $PM_{2.5}$ 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 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*** µg/m³. In street canyons with dense traffic the levels are typically doubled, ***>5*** µg/m³.

**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*** µg/m³, which is above the EU limit value. The 90-percentiles at PAR and BOQ are at about ***30*** µg/m³, i.e. compliant with EU limit values.



The concern for a possible non-compliance of the EU limit value for ***annual $NO_2$*** 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/m$^3$. For a "normal year" this would indicate an annual average well below 40 µg/m$^3$, 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 $NO_2$ levels than in 2013-2015. It is thus not to be excluded that $NO_2$ levels in street canyon may reach the EU limit value also in the coming years.

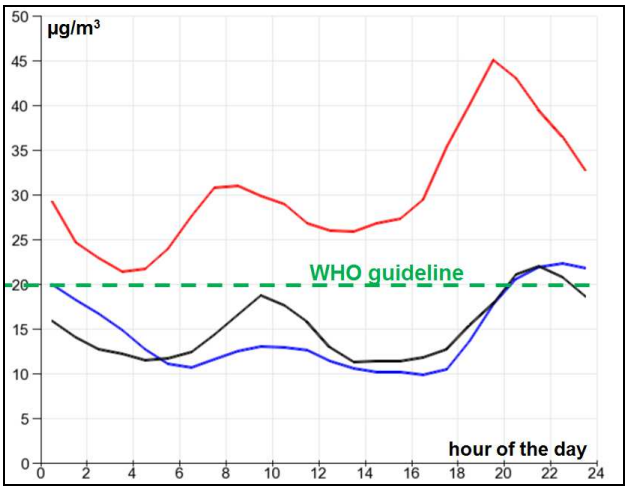
- The model simulations of NOx reveal high levels in the southwestern part of Curitiba, created by the summed impact from the traffic along the ring road and the industrial emissions in Araucária (Fig. 4.5.3). However, the model output is not sufficient for a direct comparison with the EU limit value, since it represents NOx (not $NO_2$) and constitutes only an average over one month. However, the $NO_2$ concentrations in urban background are normally rather close to NOx 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 NOx 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 25$^{th}$ July – 24$^{th}$ August, 2016.

It can not be excluded that the EU limit value of 40 µg/m$^3$ 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 ***$PM_{10}$ 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 $PM_{10}$ levels above the WHO recommended level of 20 µg/m$^3$ 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*** µg/m$^3$
- PAR: ***15.1*** µg/m$^3$
- BOQ: ***14.5*** µg/m$^3$

which can be compared to the WHO recommended value of ***20*** µg/m$^3$.

For ***$PM_{2.5}$*** the WHO recommendation or guideline is at only 10 µg/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 µg/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 µg/m$^3$, the optical instrument indicated 25.3 µg/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.

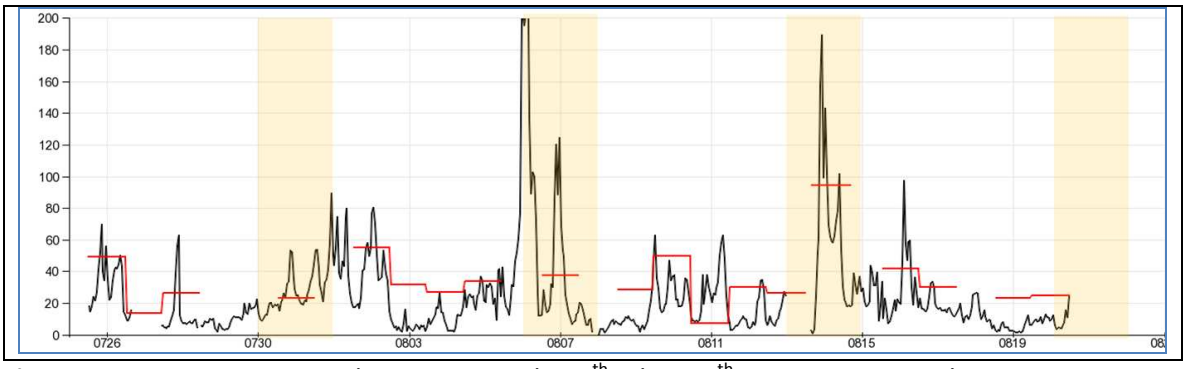


**Figure 4.5.5** PM2.5 measured at Sitio Cercado 25th July – 20th August, 2016. Daily average values from filter samples (red) gave a mean of 34.8 µg/m$^3$ and the hourly data registered by the DustTrak sampler gave a mean of 25.3 µg/m$^3$.

The $PM_{2.5}$ data collected at Sitio Cercado indicate the presence of sources to PM2.5, 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.


**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 PM10 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 µg/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 µg/m$^3$, of which half comes from local traffic exhausts. There is no emission inventory of industrial contributions to BC, but is 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 $NO_2$ 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 $NO_x$, $PM_{10}$ 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).

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Tabela 1. **Project consortium**

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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 |
| Sitio 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 Gloria (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 |

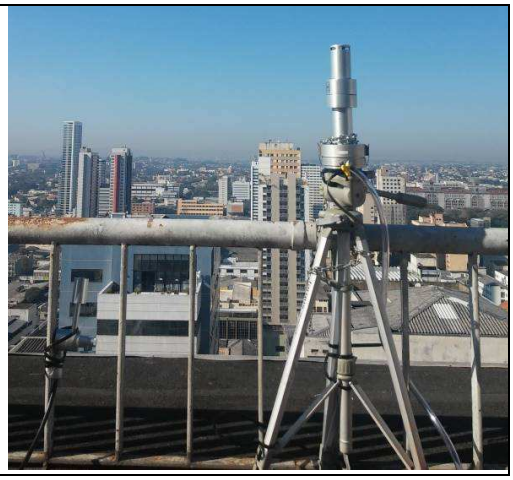

**Figure A2.1.** Instruments installed at Marechal Deodoro street canyon: street level (at about 3 m height, left) and roof level (about 70 m, right).

**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).