ITM-report 169

Characterisation and source apportionment of particulate matter in two urban areas of Chile

A project financed by SIDA/SAREC

Christer Johansson[1,2], Gustavo Olivares[1] & Lars Gidhagen[3]

[1]ITM, Stockohlm university, Stockholm

[2]Environment and Health protection administration, Stockholm

[3]SMHI, Norrköping

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1. Preface

This is the final report of a 3-year research project financed by SIDA/SAREC. The project started in 2004 and has been co-ordinated by Christer Johansson at Department of Applied Environmental Science (ITM), Unit of Atmospheric Science, Stockholm university. Other participants from Sweden has been Gustavo Olivares (PhD student at ITM), Hans Karlsson (senior engineer, ITM) and Lars Gidhagen (SMHI, Norrköping). In Chile several people have contributed to the project:

Pablo Ulriksen, Manuel Merino, Marcelo Araya and Manuel Leiva at CENMA (National Center for the Environment), Santiago

Victor Berrios at the Health Authority in Santiago.

Mauricio Ossess and Roberto Corvalan at the Mechanical Engineering Department, Universidad de Chile.

Laura Gallardo at Centro de Modelamiento Matemáco (CMM), Universidad de Chile.

Aliosha Reinoso at 3CV (Vehicle Test and Certification Center), Santiago.

Itilier Salazar at IMA (Institute for the Environment), Ufro (Universidad de la Frontera), Temuco.

Rocio Toro and Carmen Gloria of CONAMA, Temuco.

Stockholm October, 2007

Christer Johansson
Associate Professor
Unit of Atmospheric Science
Stockholm university

2. Summary

The main aim of this project has been to provide better knowledge on the characteristics of the urban air aerosol in two highly polluted cities in Chile: Santiago with around 5 million inhabitants and Temuco with less than 0.3 million people. Both cities have been declared as non-attainment zones since the PM10 levels exceed the air quality limit values. But the air pollution situation is very different in terms of aerosol emissions. The particle emissions in Santiago is dominated by road traffic activities, whereas in Temuco wood burning is a very important source apart from road traffic. Knowledge of the characteristics of the emissions and how they affect air quality is very important for cost-efficient abatement strategies and also for finding best ways minimize the effects on people's health.

This project has provided information on the urban aerosols temporal and geographic distribution, particle size distribution and estimates on the source contributions.

This project also intended to strengthen the research capabilities regarding urban aerosols in Chile. Two intensive measurement campaigns were conducted. One in Santiago and one in Temuco. Results from the project has been presented at 3 international conferences: i) the Symposium of the Nordic Aerosol Society 2005, NOSA Aerosol Symposium 2005 (Gothenburg, Sweden), ii) European Aerosol Conference 2007 (Salzburg, Austria), ii) Air pollution conference in Temuco, Chile, 2006. Two scientific manuscripts have been prepared and sent for publication. This report is mainly based on the manuscripts. In addition, results from measurements as part of this project, has been used in a master thesis: "Caracterización de la calidad del aire en una zona residencial de Temuco: fuentes y procesos atmosféricos involucrados" by Marcelo Orlando Santan Vargas, University de La Frontera in Temuco (Chile), 2005.

The measurements in Santiago included two sites: a street canyon and an urban background site. The campaign was performed during the fall-winter season, when the strongest air pollution episodes occur in Santiago. Before this study there has been very few measurements on particle number concentrations, size distribution and black carbon (BC). The average concentrations of particle number, NO_X and BC were high when compared to other urban areas. The differences between the concentrations observed in the street canyon and the urban site can be related to the distance from the emission sources as well as the impact of particle coagulation and deposition.

The particle number size distribution showed a strong nucleation mode. A secondary mode was found around 80nm. This secondary mode was found to be present both during the daytime and the nighttime, at the street canyon as well as at the urban site. BC was shown to correlate strongly with this accumulation mode observed in the particle number distribution, indicating that these particles are due to primary emissions, presumably from diesel traffic.

Inverse modelling calculations gave estimates for the emission factors for BC and particle number for heavy (HDV) and light duty vehicles (LDV). BC and particle number emission factors for HDV are substantially than those for LDV. These emission factors are comparable to previous investigations and they can be used in air quality dispersion modelling to assess the importance of primary emissions for the total particle levels. Close to traffic, in street canyons, HDV emissions seem to have a more pronounced nucleation mode, compared to LDV. Considering that health effects of particles likely depend on the size of the particles this information is important when health assessments of abatement measures are to be made.

Air quality measurements was made in Temuco (Chile) during the Chilean winter of 2005. Here the focus was on residential wood combustion. Temuco has about 210 0000 inhabitants who, according to a population survey, consumed about 28 0 000 m^3 of wood during 2002. This means 1.3 m^3 per person. As a comparison the wood consumption in Sweden as a whole is, according to official statistics, 7.3 m^3, which means 0.8 m^3 per person. But in general, wood appliances used in Temuco are of much lower quality with less heat efficiency than the appliances used in Sweden.

In Temuco, more than 50% of the houses have a cooking stove to burn wood. The cooking stove has a short start up time and it is intended to operate intermittently with intense fire while cooking and little, if any, fire the rest of the day. The heating stoves have a wide range of designs. The most common kind is similar to an enclosed fireplace with no post-combustion chamber and no air intake regulation. At the other end of the spectrum in terms of burning and heating efficiency there are the more technologically advanced stoves that are expensive and therefore not so popular. These high technology stoves have a double chamber where exhausts from the first are burnt on the second one. Furthermore, some of them have also catalytic elements to facilitate the secondary combustion.

In order to capture the large impact of residential wood combustion and be able to estimate its emission factors, we performed our measuring activities during the Austral winter fall season (April – June 2005). The results show that Temuco's air quality is greatly affected by residential wood burning. Comparing the measurements of PM10, BC, NOx and particle number with model results, we have estimated the emission factors for residential wood combustion and also for the traffic fleet of the city. The emission factors obtained with this approach are representative of an average of the wood combustion sources and an average of the vehicle fleet in the area. The size distribution of the particle number emission factor for traffic and wood combustion sources show different shapes. For traffic sources the size distribution suggests a bimodal shape with a primary mode below 50nm in diameter and a secondary mode above 100nm. For wood combustion there seems to be only a primary mode around 80nm. The features observed in the emission factor size distribution are consistent with results reported in the literature.

Using the obtained emission factors estimated the horizontal distribution of NOx and BC. The results indicated that the impact of the emissions from wood burning lead to somewhat lower maximum particle levels compared to traffic emissions, but the concentrations are distributed over larger areas of the city. The distribution of the traffic impact on PM10 levels is concentrated to the downtown area, while for wood burning there are high pollution levels in two areas, the northeast (Pueblo Nuevo, Santa Rosa) and in the west (Amanecer, Estadio Municipal, Av. Alemania, Barrio Inglés). Ambient temperature influence both the use of wood for heating purposes, as well as the dispersion conditions. During days with very low nighttime temperatures people use more wood to heat their houses. At the same time strong cooling during the night lead to strong inversions, which will cap the wood stove emissions from vertical dilution and contribute to high peak concentrations. But comparison between our measurements and model calculations based on information on the emissions, indicate uncertainties in the emission statistics of Temuco. For traffic there seem to be uncertainties in the spatial distribution of the emissions and for wood burning the average emissions might be overestimated. For future work it is of high priority to improve the knowledge of the emissions due to wood burning; checking the emission factors and the wood consumption. For the traffic source the important task is to improve the distribution of the roads in the emission data base.

Obviously, more accurate information on the emissions make assessment of abatement strategies to improve air quality much more reliable. Then air quality dispersion modelling can be a very efficient tool both for evaluation of the impact on air pollution levels and for assessing the impact on the heath of the population. Currently (2007), there is a project in Sweden with the aim to develop a system for mapping of wood burning emissions in order to make more accurate dispersion modelling of the impact of wood burning on particle levels ("VEDAIR"; http://www.luftkvalitet.se). The experiences gained from this activity might be useful also in future air pollution abatement work in Temuco.

3. Introduction

Air pollution is a major environmental health problem in both developed and developing countries around the world. Chile's economical development has had impacts in many areas, including the environment. These environmental impacts have been related to health effects by several investigations (e. g. Ostro et al, 2006; Pino et al., 1998; Ostro et al., 1999). It has been established that an increase in 50 μg/m³ of the concentration of PM10 above the Chilean standard[1] is related to an increase in 10% in the medical attentions due to respiratory illness in children younger than 15 years (Ostro et al., 1998). It has also been established an increased mortality for increases of the concentration of PM10 above the Chilean standard.

This project intended to provide detailed characterisation of the aerosol in two urban areas of Chile: Santiago and Temuco. Santiago is the largest city in Chile with nearly 40% of the country's population. It is located in a closed basin surrounded by mountains. Central Chile (where Santiago is located) corresponds to a meteorological transition zone between the Pacific High in the north and the westerly winds in the south. The average meteorological conditions are unfavourable for the dispersion of air pollutants, especially during fall and winter seasons (Rutllant and Garreaud, 1995). During these periods, the Chilean standard for PM10 is often exceeded (CONAMA, 1999) posing a risk for the population. The Metropolitan Region (Santiago and its surroundings) was declared "Saturated Zone" [2] regarding CO, ozone and PM10, which means that there is currently an attainment plan with the aim to reduce the concentrations of these pollutants in the region (CONAMA, 1999). During several days the air pollution situation in Santiago is very serious. Very high levels are recorded and the air pollution situation is described on the front pages of the main newspapers (Figure 1). Sometimes the warning system fail to predict when high levels will occur.

It has been proposed that the PM10 observed in Santiago is composed mainly of dust from primary emissions due to road traffic and secondary aerosols due to emissions from transportation and industrial sources (CONAMA, 1999), a study of source appointment for PM2.5 in Santiago showed that transport and incomplete combustion of fossil fuel are the major sources of organic compounds in Santiago's aerosol (Tsapakis et al., 2002).


EL MERCURIO

Santiago de Chile, miércoles 19 de mayo de 2004, actualizado a las 6:56 hrs.

Crisis ambiental en Santiago: Preemergencia tras falla de predicción

Pese a que para ayer sólo se decretó alerta, las estaciones de El Bosque y Cerrillos superaron los 330 puntos.
Hoy, por primera vez en el año, no pueden circular dos dígitos de autos catalíticos y seis de los sin sello verde.

A las 16:30 horas de ayer éste era el aspecto que presentaba la comuna de Huechuraba. La foto se tomó desde La Pirámide Foto HÉCTOR FLORES

La Hora

Miércoles 19 de mayo de 2004

Aire de Santiago en niveles críticos

La primera preemergencia oficial de este año vivirá hoy Santiago, luego de que los índices de contaminación alcanzaran ayer niveles críticos.
El intendente de la Región Metropolitana, Marcelo Trivelli, reconoció que el sistema predictivo falló el lunes -cuando también se debió haber decretado el estado de excepción ambiental-, pero destacó que lo importante es cómo contaminamos menos.
El modelo fue criticado por el diputado Enrique Accorsi (PPD), quien advirtió que no considera variables como la ubicación geográfica de la capital y el movimiento de los vientos.
Tampoco mide las partículas más finas y el ozono atmosférico. El experto Andrei Tchernitchin alertó que episodios críticos como el de hoy aumentan la mortalidad, que "pueden crecer al doble".

Figure 1. Newspaper headlines describing the air pollution situation in Santiago, Chile (2004).

But Santiago is not the only city in Chile with air pollution problems. Temuco, located 600 km south of Santiago is also affected by high levels of PM10. The problem is not as severe in Temuco as in Santiago but the levels observed are also above the Chilean standard for PM10. Studies have proposed that wood burning and road traffic are the most important sources of organic aerosols in the PM2.5 fraction (Kavouras et al., 2001; Tsapakis et al., 2002). The high levels of

[1] 150 μg/m³ for the 24hr average

[2] In Chilean legal term that means that the concentrations observed in an area exceeds the current regulatory level.

PM10 have lead the authorities to declared Temuco a “Saturated Zone” regarding PM10. An example of an air pollution episode in Temuco is shown in Figure 2.

Figure 2. Air pollution episode in Temuco, Chile (May, 2005).

4. Objectives

This overall objective with this project has been to increase the knowledge on the emissions and concentrations of the urban aerosols. The intention has been to provide a better basis for more effective abatement strategies and health effect assessments of airborne particles in Santiago and Temuco. This characterisation includes:

- The temporal and geographic distribution
- The particle size distribution
- The source contributions

This project was also intended to strengthen the research capabilities in Chile. There is an extensive experience and knowledge at the Chilean universities studying particulate matter in terms of mass but, no efforts have been made to study the number size distribution in Chile (e.g. CENMA, 1999; Kavouras et al., 2001). On the other side, ITM (Stockholm university) has an important experience in measuring and modelling urban aerosols in terms of its number size distribution (Johansson et al., 2001; Johansson et al., 2007; Gidhagen et al., 2003b; Gidhagen et al., 2005). Therefore, this project was intended to transfer knowledge of measuring particle number and size distribution and aerosol modelling. The participation of Chilean students in this project have improved the exchange of knowledge by contributing to the growth of the Chilean scientific community related to atmospheric aerosols.

5. Research co-operation

The main contact institution was **CENMA**. This institution, Centro Nacional del Medio Ambiente (National Center for the Environment, www.cenma.cl), is part of the Universidad de Chile and in its 10 years of life it has participated in most of the environmentally related projects in Chile. CENMA is in charge of managing the air pollution monitoring network in Santiago. Moreover, it is participating in a current epidemiological study in Santiago that will continue for another two years, relating atmospheric concentrations of pollutants and health effects.

Another institution that participated in this project is **CMM**. This institution, Centro de Modelamiento Matemático (Mathematical Modelling Centre, www.cmm.uchile.cl), is part of the University of Chile (UCHILE) and it is devoted to work in applied mathematics. The motivation of the CMM into this project comes from their interest to start aerosol modelling. The CMM has a large computational capacity to run the dispersion and aerosol models.

A third institution that cooperated in this project is the **PUC**, Pontificia Universidad Católica de Chile (Catholic University of Chile, www.puc.cl). PUC cooperate with the regional environmental authority in Santiago (CONAMA-RM). They use a web version of the AIRVIRO system with the information of the air pollution network and emission database in Santiago (see www.smhi.se for info on AIRVIRO).

During the campaign in Santiago one activity was the training of personnel from Universidad de Chile (Mauricio Osses) and 3CV (Centro de Control y Certificacion Vehicular) in atmospheric particle measurements, aside of emission testing which is what they normally do.

Finally, close contacts have been established with key people at the Universidad de la Frontera, www.ufro.cl, (UFRO). **UFRO** is the most important academic entity in the area of Temuco and it has a growing interest in environmental initiatives, reflected in the creation of the Environmental Institute (Instituto Del Medio Ambiente, IMA www.ima.ufro.cl). Moreover, UFRO has created the Modelling and Scientific Informatics Center (Centro de Modelación y Computación Científica, **CMCC**) within the Department of Mathematics, with the aim to generate knowledge and expertise regarding mathematical modelling and scientific informatics. The CMCC has implemented the Karlsruhe Atmospheric Mesoscale Model (KAMM, http://www.risoe.dk/ita/regneserver/projects/kamm.htm). With this model the CMCC provided the meteorological information required to run the atmospheric dispersion model for the area of Temuco.

6. Santiago campaign

In this report a summary of all activities and results from the measurements and modelling in Chile is presented. This report is mainly based on two manuscripts that have been submitted for publication in Atmospheric Environment and The Science of the Total environment (Olivares et al., 2007a; Olivares et al., 2007b). The results of the measurements in Temuco have also been presented at a conference on air quality in Temuco (Olivares et al., 2005).

6.1 Measurement sites in Santiago

The measurements in Santiago took place between May 15th and July 1st 2004 at two sites. One in a street canyon in the city centre (Teatinos) and one in a park (The Parque O'Higgins) in downtown Santiago (see Figure 3& Figure 4).

6.1.1 Parque O'Higgins

The Parque O'Higgins station is part of the monitoring network of the Metropolitan Region of Santiago maintained by the Metropolitan Health Authority. This station is located in a park in the centre of the Santiago basin, about 4 km southwest of the Teatinos site. The station is in an open area more than 800m from the closest road and about 300m from the nearest trees. This station collects information regarding PM_{10}, $PM_{2.5}$, CO and ozone (Silva and Quiroz, 2003). Also, the particle counter system "EMMA" was installed in this site. This system consists of two CPC (TSI – 3010), a DMA system (10 channels between 20nm and 120nm), an OPC particle size spectrometer (8 channels between 100nm and 3200nm) and a PSAP. One of the CPCs is used as total counter for particles larger than 10nm in diameter. The second CPC is used in connection with the DMA to obtain a particle number size distribution between 20nm and 120nm. The OPC is used to obtain the particle number size distribution between 100nm and 3μm. Thus, these instruments give as a result a particle number size distribution from 10nm up to 3μm, and BC concentration every 6 minutes. The difference in sampling frequency with the Teatinos site is due to different logging systems in use at each site.

Figure 3. Measurement installations in Parque O'Higgins, Santiago.

6.1.2 Teatinos

The Teatinos street canyon is 15 m wide and it has buildings ca 25 m high on each side making it representative of a street canyon site. The traffic flow in this street is from north to south with an average of 20 000 vehicles per day with a large difference between the rush hours (ca 1300 vehicles hr^{-1}) and the nighttime (ca 100 vehicles hr^{-1}). Vehicle composition was counted manually at several times during the day. These traffic counts were used to adjust and normalize the traffic information available from the traffic model ESTRAUS from the Transportation Authority (Corvalan et al, 2002).

Two sets of instruments were located in this canyon. At about 6m above the pavement, a first set of instruments was placed. Particle number size distribution from 16nm to 400nm in diameter was recorded using a differential mobility analyser (DMA) constructed at ITM connected to a commercial condensation particle counter (CPC – TSI 3760). A detailed description of this instrument is given by Olivares et al (2007a). Black carbon (BC) was measured with a custom built Particle Soot Absorption Photometer (PSAP) installed in parallel with the DMA system (Krecl et al., 2007).

The second set of instruments was installed on the roof of the western side of the canyon, pointing into the street canyon. It consisted of a CPC (TSI – 3022) measuring total particle number concentration (N_7; particle diameter >7nm) and a PSAP for BC. Also, a chemiluminescence NOx sensor (T-API, model 200A) was set up in the lower site.

Figure 4. Measurement installations at Teatinos, street site (CONAMA), Santiago. Left shows installation inside the toilet and right picture shows the street canyon of Teatinos.

6.1.3 Other measurement data

The Chilean Metropolitan Health Authority for Santiago, made available for this study the information from Santiago's monitoring network (Silva and Quiroz, 2003). This network consists of seven stations distributed in the urban area of Santiago. The parameters measured in those stations are PM10, PM2.5, CO, Ozone, NOx. The Chilean National Centre for the Environment (CENMA) performs routine checks and calibrations of all the instruments within the Santiago monitoring network (Silva and Quiroz, 2003).

6.2 Results from measurements in Santiago

Figure 5 shows the median diurnal variation of the observed parameters during the campaign. During working days, the observed variation in measured parameters reflects the impact of activities within the city. In the street canyon, NOx, BC and $N_{16\text{-}400}$ show a similar variation with higher concentrations during the daytime compared to the night. Also, two maxima are evident that coincide with the morning and evening rush hours. During weekends (Sunday), the morning maximum is not present but there is an increase of the ambient concentrations in the evening. This increase may be related to an increase in the traffic flow in this street on Sunday evenings when people return to their homes after leisure activities.

Comparing the concentrations in the street canyon with those measured in the urban site, the concentrations observed in the street canyon are higher than those measured in the urban site.

This was expected because while the urban site is intended to represent the air quality of the central part of the city, the street canyon sites are closer to the traffic emission sources and therefore expected to measure higher concentrations than at the urban site.

The differences, however, are not the same for all components. For NOx, the average concentration observed in the street canyon is about 4 times higher than that measured in the urban site. For particle number and BC the concentrations in the street canyon are about 12 times higher than in the urban site. There are a number of possible reasons for the larger difference in concentrations of BC and N compared to NOx between the sites. One reason can be that whereas NOx is relatively inert on an urban scale and mainly affected by atmospheric dilution, particulate matter (BC and N) is affected not only by atmospheric dilution.

Particle number concentration is affected by aerosol dynamics processes such as nucleation, coagulation and dry deposition that modify the size distribution from the source and affect the total number concentration.

As it is shown in Figure 5, the particle number size distribution in the urban background does not present as large a nucleation mode as the size distribution in the street canyon. Ketzel and Berkowicz (2005) showed that this difference is related to the impact of coagulation, deposition and condensation on the particle size distribution. These processes have been shown to act in a similar way, removing mainly nucleation mode particles. In this way, they decrease the total particle number concentration and change the shape of the particle number size distribution. Therefore, these processes enhance the difference in concentration between the street canyon and urban site measurements. Regarding BC, the impact of these processes is expected to be small because BC is associated with particle sizes within the accumulation mode (~100nm).

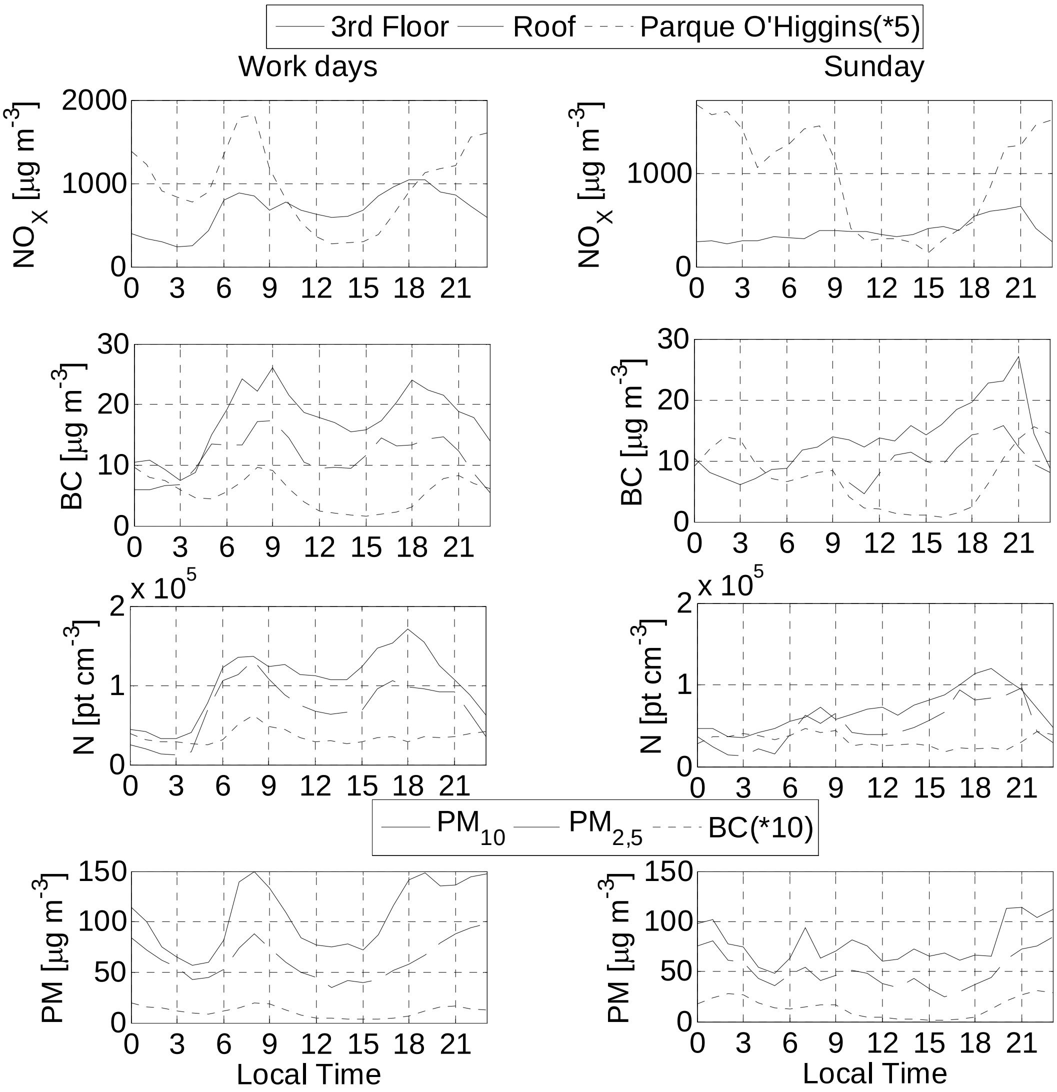


Figure 5. Diurnal cycle for weekdays and Sundays of the measured parameters in the Street canyon and at the urban background. The left panels correspond to the week day variation and the right panel to the Sunday variation. As indicated in the figure, the first panels correspond to NOx, the second to BC and the third to N for the street canyon and the urban background. Note that the urban background concentrations are scaled up by a factor of 5 for clarity of the figure. The last panels correspond to the particle matter concentrations (PM_{10}, $PM_{2.5}$ and BC) measured in the urban background site. Note that the BC concentrations in the lower panels are scaled by a factor of 10 for clarity of the figure.

Figure 6 shows the average particle number size distribution for daytime and nighttime in the street canyon and in the urban background. Particle number size distributions show a distinct nucleation mode in the street canyon measurements. A secondary mode (Dp~100nm) is apparent both in the street canyon and at the urban site. This accumulation mode was shown to correlate strongly with black carbon (BC) (r>0.8), measured using an optical absorption photometer.

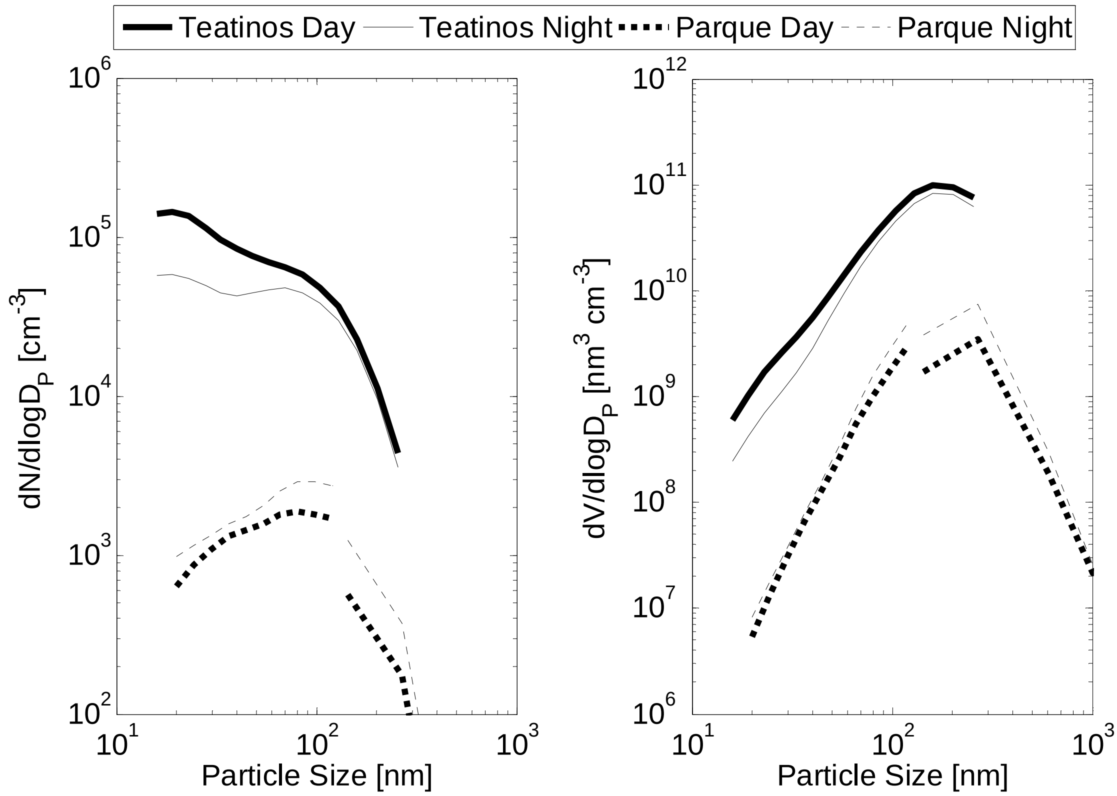


Figure 6. Particle number and volume size distribution measured at the street canyon and at the urban background site. The dashed lines correspond to the urban background and the solid lines to the street canyon. The heavy lines indicate daytime values (07:00 – 19:00) and the thin lines indicate nighttime values (20:00 – 06:00). The lines for the Parque O'Higgins station present a discontinuity because there were two instruments measuring the number size distribution, a DMPS for 20nm<Dp<120nm and an OPC for Dp>140nm.

The public transportation fleet in Santiago consists of 100% diesel busses and half of them are more than ten years old (CONAMA, 2003). Direct diesel particle emissions have been shown to present a carbon-related mode between 60nm and 100nm (Kittelson et al, 2006). Therefore, it is reasonable to think that the number mode observed in the particle size distribution is also related to the BC concentrations. To test this hypothesis, a correlation analysis was performed between the particle size distribution and BC. Hourly concentration for each size bin was treated as an independent variable and correlated with BC (See Figure 7).

A maximum in the correlation coefficient between BC and particle number is observed around 100nm both in the street canyon and in the urban background. This maximum roughly coincides with the accumulation mode. This suggests that soot emissions from are associated to accumulation mode particles both at the street canyon and at the urban site. This is consistent with the hypothesis that diesel particle emissions are responsible for a large fraction of this mode. The higher values of the correlation factor at the urban site can be related to dilution and transport effects. Coagulation, condensation and deposition will decrease the concentration of nucleation mode particles (Ketzel and Berkowicz, 2005). Therefore, particles with sizes around 100nm have a longer life time than nucleation mode particles in the urban atmosphere and contribute more to the observed variability of the particle number concentration in a site far from sources, than in a street canyon.

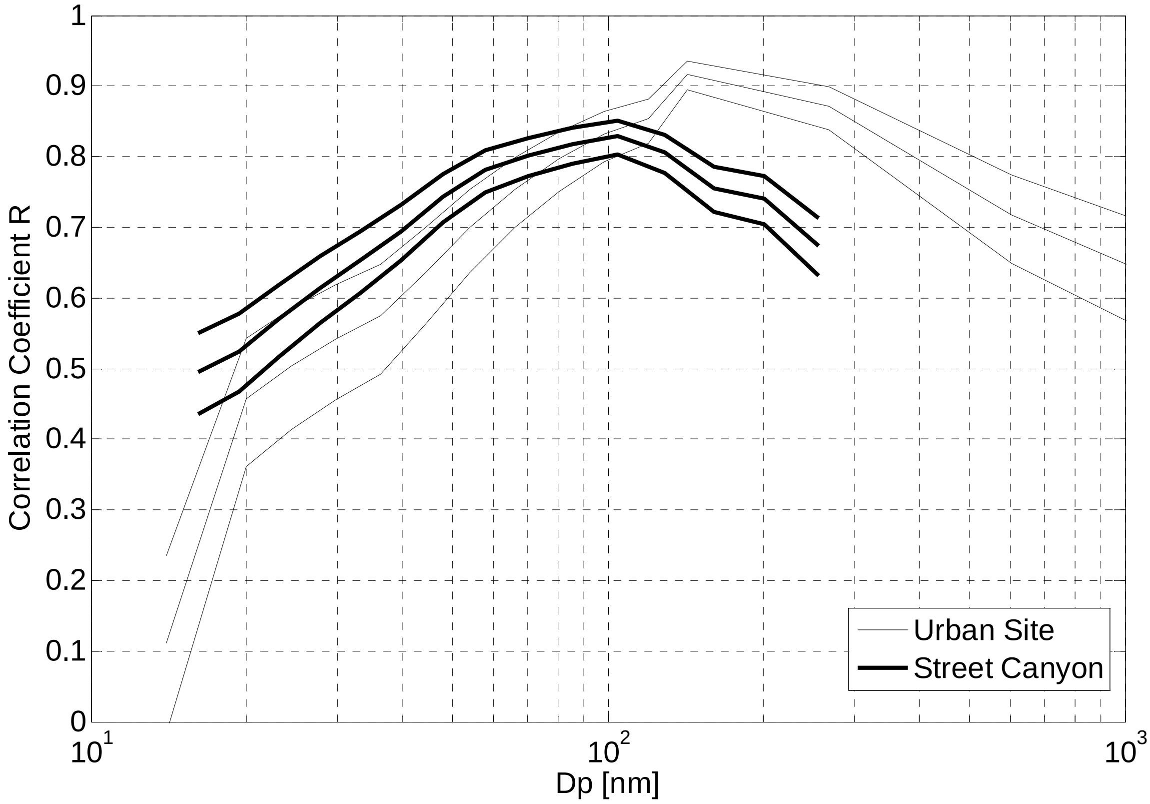


Figure 7. Correlation coefficient between BC and the particle number size distribution at the street canyon (heavy lines) and at the urban site (light lines). The upper and lower lines for both sites correspond to the 95% confidence interval of the correlation coefficient.

6.3 Estimation of emission factors in Santiago

To obtain the emission factors, the Operational Street Pollution Model (OSPM) was used. This model is a parameterized street canyon air pollution model that is used for air quality management in urban areas. A detailed description of the model is given by Berkowicz (2000). The model takes advantage of a large number of experimental data and modelling results to describe the relationship between the emissions and measurements at a particular location in the street. These parameterizations include the geometry of the canyon, the wind conditions aloft and the traffic intensity in the canyon. This model was implemented for the Teatinos street canyon with the wind information from the closest meteorological station. The traffic fleet information was obtained from the Transit Authority (Corvalan et al, 2002), adjusted according to the results of our manual counts.

Diesel Buses correspond to 30% of the total traffic flow (CENMA, 1999) with an average emission factor of 10 g NOx $veh^{-1}km^{-1}$ (Corvalan et al, 2002). For the rest of the fleet, mainly light duty vehicles (LDV), an average emission factor of 1.1 g NOx $veh^{-1}km^{-1}$ was used (Corvalan et al, 2002). These emission factors were implemented in the OSPM model. Figure 4 shows the comparison between the modelled and the observed NOx concentrations in the street canyon.

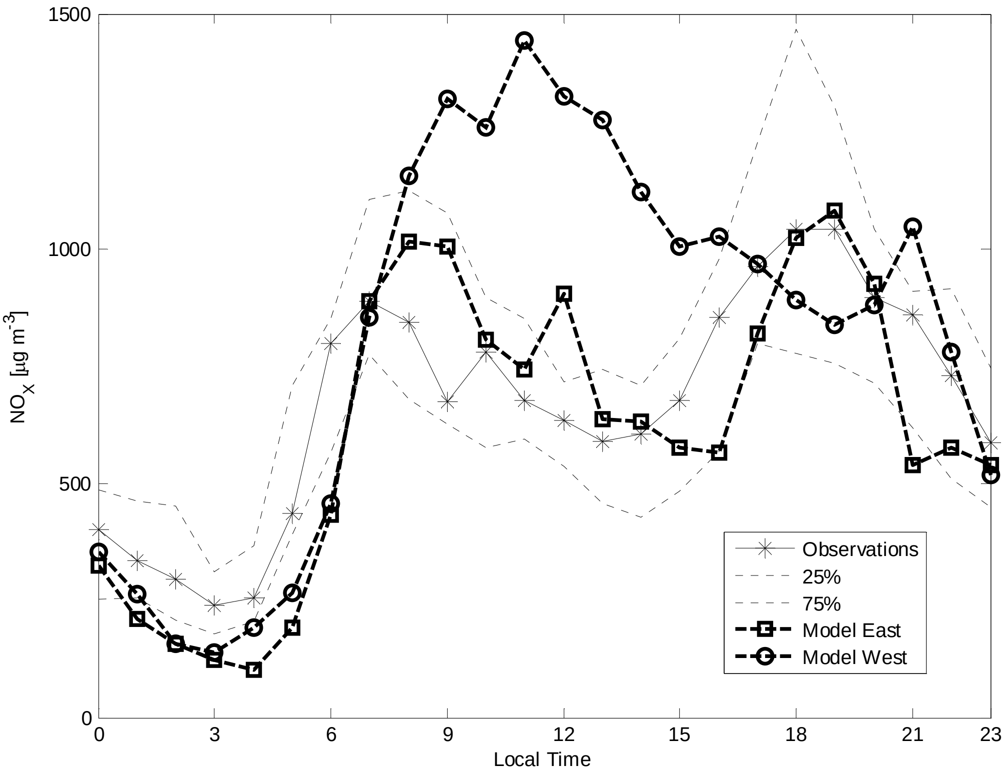


Figure 8. Measured and modelled diurnal variation of the NOx concentrations in the street canyon. The solid line with stars indicates the observations. The dashed thin lines correspond to the upper and lower quartiles of the measured data. The heavy lines with symbols indicate the modelled concentrations for the east and west side of the street canyon. The measurement point was located on the west side of the street.

The model is able to capture the average daytime and nighttime NOx concentration in the street canyon. However, during daytime, the model gives too high concentrations for the western side of the street (measurements side) and a better agreement between the observations and the eastern side of the street. This may be related to the low wind speeds observed during the campaign (mean: 1.7 m s^{-1}; σ: 1.2 m s^{-1}) and the geometry of this particular street canyon. Model calculations have shown that in narrow street canyons, low wind speeds may induce several detached vortices in the street canyon air flow (Baik and Kim, 1999). This condition is not considered by the OSPM model. Therefore, the average results from the eastern and western side of the street will be used. However, considering the uncertainties in the input information to the model, such as the HDV/LDV classification, the result seems encouraging for the purposes of estimate the average emission factors for BC and particle number.

To obtain an estimate of the BC and particle number emission factors for the Teatinos fleet, the OSPM model was run and the emission factors were adjusted to fit the time series of the BC concentrations in the street canyon. As indicated before, during daytime, the concentrations measured in the street canyon are much higher than in the urban site, therefore, for the emission factor analysis, only daytime data will be considered. With the information available about the diurnal variation of the traffic composition, emission estimates were found for Heavy Duty Vehicles (HDV – Buses) and Light Duty Vehicles (LDV – other vehicles). Table 2 shows the results of the fitting processes for BC and particle number as they compare to emission factor estimates from the literature.

Table 1. Comparison of particle number and black carbon emission factor estimated in this work with those obtained in previous studies. The total fleet emission factor was calculated considering 30% HDV for the lowest and highest estimate for HDV and LDV for each study. The uncertainty ranges for this study are given for the 95% confidence interval of the emission factor estimates.

Parameter	Method	Units	LDV	HDV	Fleet (30%HDV)	Reference
BC	PSAP	[μg ve^{-1} km^{-1}]	68±26	96±90	77±46	This study
BC	Aethalo-meter	[μg ve^{-1} km^{-1}]	9.2 – 10	114 – 427	41 – 135	Imhof et al, 2005
BC	Aethalo-meter	[μg ve^{-1} km^{-1}]	1.6	122	38	Weingartner et al, 1997
BC	Various	[μg ve^{-1} km^{-1}]	60-300[1] 2-7[3]	160-525[2] 32-64[4]	90-370 11-24	Kupiainen and Klimont, 2004
N_{16-400}	DMA	10^{14} [ve^{-1} km^{-1}]	3.3±0.7	7.5±2.5	4.6±1.3	This study
N_{8-300}	DMA	10^{14} [ve^{-1} km^{-1}]	0.34±0.05	6.6±1.0	2.2±0.3	Johnson et al, 2005
N_3	CPC	10^{14} [ve^{-1} km^{-1}]	6.2±1.4	42±6	17±2.8	Johnson et al, 2005
N_7	CPC	10^{14} [ve^{-1} km^{-1}]	0.8 – 6.9	55 – 73	17 – 27	Imhof et al, 2005
N_{10}	CPC	10^{14} [ve^{-1} km^{-1}]	1.1 – 5.9	58	18 – 22	Gidhagen et al, 2003a
N_{10}	CPC	10^{14} [ve^{-1} km^{-1}]	0.41	25	7.8	Kirchstetter et al, 1999

[1] Diesel, no control.
[2] No control
[3] Gasoline
[4] Controlled

Information about BC emission factors is scarce and the comparison is difficult due to the different measuring methods used in the different studies. Also the share of gasoline versus diesel LDV may vary. This can be very important since gasoline vehicles have lower emission factors than diesel vehicles, especially if they have no exhaust control. Table 2 shows results only from optical measurements (except Kupiainen and Klimont, 2004, which is a review of many studies on BC emission factors) to make them more comparable to the results obtained in this study. The HDV emission factor obtained in this work is within the reported value. Note that the 95% confidence interval of the BC emission factor for HDV in our study is very large. This is due to the uncertainties in the traffic data information. Considering LDV, the BC emission factor estimate is more than a factor of 3 larger than previous estimates. This may be related to a higher share of diesel vehicle with no exhaust emission control. It may also be due to the assumption about the specific absorption coefficient for the BC measurements, but without information about the Santiago aerosol, it is not possible to estimate its impact.

Furthermore, as well as for HDV, the large differences with previous studies may be related to the uncertainties in the traffic information. In fact, the available information about the fleet composition in the street canyon only discriminates buses from the total fleet. Thus the LDV emission factors are likely to be overestimated because of the impact of other HDV that are not buses and are considered as LDV in this study. For the same reason the HDV emission factors are possibly underestimated.

For particle number, on the other hand, the main difficulties come from the size range considered in the studies. This is particularly evident in the results reported by Johnson et al (2005) where the emission factors obtained from the DMA (8nm<Dp<300nm) are almost one order of magnitude smaller than those obtained from the CPC (Dp>3nm). Therefore, it was to be expected that our estimates would be on the lower end of the reported emission factors.

Applying the same methodology, the size distribution of the particle number emission factor both for HDV and LDV was estimated (Figure 9).

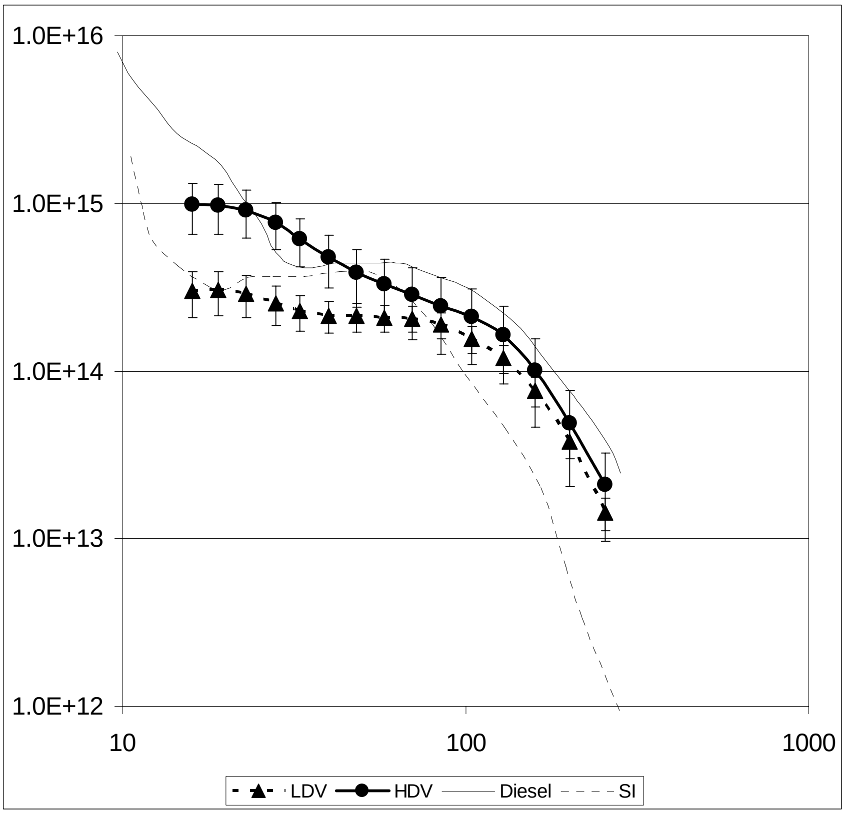


Figure 9. Size distribution of the particle number emission factor for LDV (--▲--) and HDV (–●–). The error bars correspond to the 95% confidence interval of the emission factor estimates. Results from Johnson et al (2005) are also shown for comparison (thin lines for diesel and spark ignition vehicles). The units are ve^{-1} h^{-1}. The results from Johnson et al (2005) were originally fuel specific, in units of [kg^{-1}], and they were converted using a fuel economy of 10 km l^{-1} for LDV and 2 km l^{-1} for HDV into [ve^{-1} km^{-1}].

Previous studies have shown that the size distribution of the particle number emission factor has a rather large variability depending on the sampling and driving conditions. Kristensson et al (2004) showed higher particle number emission factors for higher vehicle speed. Furthermore, Kittelson et al (2006b) showed that for spark ignition (SI) vehicles, the particle number emission factor for particles around 100nm is one order of magnitude larger for cold start vehicles compared to warm vehicles. For particles around 10nm the difference is about a factor of 2. For diesel engines, Kittelson et al (2006a) showed that the emission factor for accumulation mode particles (Dp~100nm) is similar irrespective of the diving conditions or measurement technique. However, for particles smaller than 20nm, there is a large variability depending on the sampling and driving conditions.

Figure 9 shows that the estimates for the fleet in Teatinos street canyon are consistent with previous studies, particularly the HDV estimates, even with studies carried out with newer vehicles. This may be related to the lower speed observed in Teatinos (ca 30 km hr^{-1}) as compared to other studies (80 – 90 km hr^{-1}; Kittelson et al, 2006a,b).

6.4 Conclusions from measurements and modelling in Santiago

The measurements in Santiago included two sites: a street canyon and an urban background site. The campaign was performed during the fall-winter season, when the strongest air pollution episodes occur in Santiago. The average concentrations of particle number, NO_X and black carbon (BC) were high when compared to other urban areas. The differences between the concentrations observed in the street canyon and the urban site can be related to the distance from the emission sources. This difference is larger for ultrafine particles due to the impact of coagulation and deposition.

The particle number size distribution showed a strong nucleation mode. A secondary mode was found around 80nm. This secondary mode was found to be present both at daytime and nighttime, at the street canyon as well as at the urban site. BC was shown to correlate strongly with this accumulation mode observed in the particle number distribution, indicating that it originates from primary exhaust emissions.

Inverse modelling calculations gave estimates for the emission factors for BC and particle number for heavy (HDV) and light duty vehicles (LDV). BC and particle number emission factors for HDV are substantially than those for LDV. These emission factors are comparable to previous investigations. However, differences in the measuring technique and the traffic classification make comparison with other studies difficult. HDV emissions seem to have a more pronounced nucleation mode, compared to LDV in the Teatinos street canyon. However, lack of information on the traffic composition and volume make the evaluation of the differences between HDV and LDV very uncertain.

7. Temuco campaign

Biomass burning has a severe impact on the air quality in several parts of the world, particularly in developing countries (Ludwig et al., 2003). Emissions from biofuels have been reported to be of similar magnitude as those from open vegetation fires (Ito and Penner, 2004). Emissions from residential wood combustion are difficult to characterize due to the small scale and scattered nature of these sources and the range of fuels used. Using air quality measurements from a campaign in Temuco (Chile) during the Chilean winter of 2005, we estimated the size resolved particle number emission factors from residential wood combustion. These estimates correspond to an average of the equipments used in the city and an average of the operating conditions in terms of quality of fuel and burning conditions.

In total Temuco and Padre las Casas (small city close to Temuco in the same domain with regard to air pollution impact) has about 340 0000 inhabitants who, according to a population survey, consumed about 28 0 000 m^3 of wood during 2002 (CONAMA, 2002). This means around 7 m^3 per house according to an estimate made by CONAMA (Carmen Gloria, personal communication, 2007). Figure 10 show estimates for several cities in Chile for comparison. The wood consumption will depend on climate, price and availability of wood.

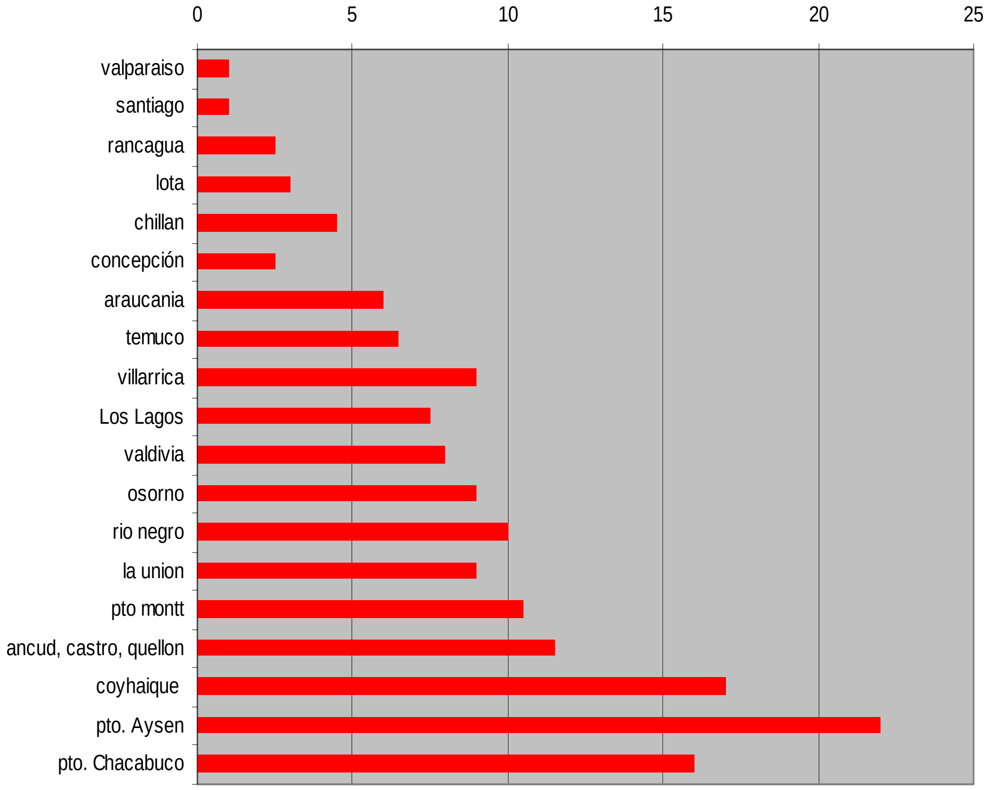


Figure 10. Estimated annual consumption of wood per house (m^3) in different cities in Chile. From Carmen Gloria (CONAMA RM, Santiago, Chile). The cities are ordered from north (warm climate) to south (colder) in Chile.

The appliances used in the Temuco area are of three types: Cooking stoves, heating stoves (Figure 11) and open fireplaces. There are several differences between the three appliances and they differ in popularity in the Temuco area. More than 50% of the houses have a cooking stove, ca 40% have a stove for cooking and less than 1% of the houses have an open fireplace. The difference in distribution is related to the household income. Fireplaces are the most expensive and require a rather large house to be built.

In terms of burning processes, the cooking stove has a short start up time and it is intended to operate intermittently with intense fire while cooking and little, if any, fire the rest of the day. The heating stoves have a wide range of designs. The most common kind is similar to an enclosed fireplace with no post-combustion chamber and no air intake regulation. The thermal efficiency of the most common stove for heating is 40%-50%. At the other end of the spectrum in terms of burning and heating efficiency there are the more technologically advanced stoves that are expensive and therefore not so popular. These high technology stoves have a double chamber where exhausts from the first are burnt in the second one.

Figure 11. Typical stoves used in Temuco. Right: stove for heating with a thermal efficiency of 50%-60%. Left: typical stove for cooking.

However, the high water content of the wood used in Temuco means that none of these technologies work within optimal conditions and are likely to have larger emissions of particulate and gases than the expected. With this consideration, the environmental authority has begun an education campaign to promote the use of dry wood to improve the operation of the appliances (Figure 12).

Figure 12. Poster informing the people in Temuco of to use dry wood from wood markets (instead of wet wood) in order to keep the air clean.

The fall-winter season in Temuco is characterized by two contrasting meteorological situations (Miller, 1976). First, when frontal systems pass over the area, there is intense rainfall with relatively high winds that lead to efficient dispersion of the surface emissions. The second situation is observed between the passing of frontal systems and it is characterized by clear skies, low temperatures, low wind speeds and increased atmospheric stability. This increased atmospheric stability during cold periods means that the larger emissions from residential heating during these periods are poorly dispersed in the atmosphere and therefore there is an increase in the ambient concentrations of atmospheric pollutants. Therefore, in order to capture the large impact of residential wood combustion and be able to estimate its emission factors, we performed our measuring activities during the Austral winter fall season (April – June 2005).

7.1 Measurement sites in Temuco

The measurements were carried out at two sites between April 18th and June 15th of 2005. One urban background site, and one site in the city centre.

7.1.1 Las Encinas

The Las Encinas site is the official regulatory air monitoring site in Temuco. This means that its measurements are supposed to be representative of the whole city and are used to determine if attainment measures are required. The station is located in an open field (ca 200x200 meters) southwest of the city (Figure 13). The field is surrounded by residential areas and only smaller roads with <500 vehicles per day. The station located here provides hourly concentrations of PM10 (Beta gauge Environnement S.A., MP101M), NOx (Environnement S.A., AC32M), CO (Environnement S.A., CO12M) and meteorological parameters such as wind, ambient temperature and relative humidity. This station is calibrated and maintained by the health authority through the National Center for the Environment (CENMA, CONAMA, 2004). The particle number measuring system "EMMA" was installed in this site for the whole campaign. This system uses two Condensation Particle Counters (CPC), one Optical Particle Counter (OPC), one Differential Mobility Analyzer (DMA) and a Particle Soot Absorption Photometer (PSAP) to give as a result particle number concentration (N10), size distribution from 10nm up to 3µm, and BC concentration every 6 minutes. This system is described in detail elsewhere (Olivares et al., 2007a).

Figure 13. Urban background measurement site at Las Encinas, Temuco.

7.1.2 Temuco City

During the first six weeks of the measuring campaign a set of instruments was located at a busy street in downtown Temuco. This street has an orientation of 78 degrees from the north to the west. The traffic flows from east to west on two lanes. Manual traffic counts gave a daily average of 7500 vehicles, with an average maximum flow of 500 veh hr^{-1} at rush hour (09:00), and an average minimum at nighttime of 30 vehicles hr^{-1}. According to the official estimates, the traffic composition is about 10% heavy duty diesel vehicles, all of them buses (CONAMA, 2002). Our instruments were placed on a balcony about 4m above the pavement, with the sampling tube stretching to the edge of the street. The instruments included a custom built Differential Mobility Analyzer (DMA) running in a scanning mode with a scanning time of two minutes for a particle number size distribution of 20 bins from 25nm to 680nm in diameter. The DMA was connected to a condensation particle counter (CPC – TSI 3760). The mobility distribution measured by the DMA system was inverted to a number distribution assuming a Fuchs charge distribution and charge correction for single and double charged particles (Wiedensohler, 1988). Black carbon (BC) was measured with a custom built Particle Soot Absorption Photometer (PSAP) installed in parallel with the DMA system. This PSAP logged information every one minute. Also, a chemiluminescence NOx (Environnement S.A., AC31M) sensor was set up in parallel with the particle measuring system. The instruments were calibrated and maintained at the Department of Applied Environmental Sciences - Atmospheric Sciences Unit - Stockholm University prior to the campaign and checked for consistency afterwards. Furthermore, PM10 measurements were carried out during one week with an integrating nephelometer (Thermo, DR-1000) supplied and maintained by the Chilean National Center for the Environment. This instrument was calibrated against the PM10 measurements at Las Encinas during two weeks of the campaign.

As indicated above, BC was measured with PSAPs. A detailed description of the instrument is given by Reid et al. (1998). Our instruments operate with a wavelength of 525 nm. The raw data from the PSAPS was filtered with a running average of five minutes and cleaned from discontinuities (occurring when changing filter substrate). To obtain the BC concentrations in µg m-3, we need information regarding the specific absorption coefficient (σ). Several authors have reported values of σ between 5 and 20 m2 g-1 for PSAPs under various conditions, including biomass burning (Martins et al., 1998; Marley et al., 2001; Sharma et al., 2002). Measurements performed in Sweden with identical instruments indicate that, for residential wood combustion, a specific coefficient of 20 m^2 g^{-1} gives similar concentrations as thermal measurements methods (Krecl et al., 2006).

The raw data was filtered with a 5 minutes running average and then 15 minutes values were calculated to use as base information to calculate hourly averaged concentrations.

7.2 Results from measurements in Temuco

Basic statistics of ambient concentrations of nitrogen oxides (NOx), PM10, PM2.5, black carbon (BC) and particle number (N_X, the sub index indicates the lower cut-off size, X nm) are shown in Table 2. These statistics include the mean, standard deviation, median, upper and lower quartiles of the daily averages, as well as the number of days considered in each value.

The concentrations observed in Temuco are in the range of other cities (e.g., Querol et al., 2001; Bogo et al., 2003; Celis et al., 2004). However looking at the ratios between some of the pollutants, the impact of different meteorological dispersion conditions is cancelled out and the influence of the different sources becomes more evident. At the street site the ratio NOx/BC is more than 40 g NOx/g BC, while at the urban background site this ratio is around 15 g NOx/g BC. These values may be compared with the ratio of the emission factors for traffic sources and wood combustion. According to the literature, the ratio of the emission factors is around 20 g NOx/g BC for traffic sources (Corvalan et al., 2002; Olivares et al., 2007a). For wood burning sources the ratio is around 1 g NOx/g BC (Larson and Koenig, 1993).

Table 2. Statistics of the of the air quality during the measurement campaign. Median, upper and lower quartiles and number of days with valid data for the variables measured during the campaign. The statistics were calculated from 24-hours daily values.

Location	*Parameter*	*Mean*	*StdDev*	*Median*	*25%*	*75%*	*Days*
Las Encinas (urban)	NOx [μg m^{-3}]	38	21	35	21	51	80
	PM_{10} [μg m^{-3}]	68	48	56	34	91	78
	PM_{10} [μg m^{-3}]*	45	20	38	32	53	8
	BC [μg m^{-3}]	2.6	2.3	1.8	1.1	3.5	64
	N_{10} [cm^{-3}]	22700	14200	18600	12700	29900	41
City (street)	NOx [μg m^{-3}]	134	56	139	95	185	34
	PM_{10} [μg m^{-3}]	37	13	38	29	44	8
	BC [μg m^{-3}]	3.1	2.0	2.6	1.8	4.0	41
	$N_{25\text{-}500}$ [cm^{-3}]	31200	17200	27500	20200	37800	25

* *Only during the period where there were PM10 measurements at both sites.*

Similarly, the ratio of particle number (N) over NOx should be related to the ratio in emission factors for the corresponding dominating source at each site. From Table 2, this ratio is more than 600 [pt pgNOx^{-1}] for Las Encinas but only about 200 [pt pgNOx^{-1}] for the City site. Measurements in Stockholm and Santiago indicate that a ratio between 200 and 400 is related to road traffic sources (Olivares et al., 2007a; Olivares et al., 2007b). For wood combustion, emission factors for the ratio (N/NOx) are almost one order of magnitude higher than for traffic sources (Larson and Koenig, 1993; Hedberg et al., 2002). This is consistent with the hypothesis that Las Encinas is representative of residential wood combustion while the city site is representative of traffic sources. Note that since the statistics presented in Table 2 were calculated using daily averages, the standard deviation and percentiles refer to the day-to-day variability and not the variations within a day.

Figure 14 shows the median diurnal variation for the measured pollutants in Las Encinas and in the City sites for workdays and Sundays. Sundays were chosen to be representative of a situation

* Only during the period where there were PM10 measurements at both sites.

when there are low emissions. Saturdays are not shown because they correspond to a situation in between workday and Sunday in terms of urban activity. The first row in Figure 14 shows the NOx concentrations, the second corresponds to BC and the third shows the total particle number concentrations (N25-500 for both sites).

As expected, the concentrations measured during the weekends are lower than during working days and they show a smaller variation from day to nighttime. During nighttime, the concentrations in the urban site are of similar magnitude as those in the City. During daytime, the largest differences are observed for NOx and BC, while particle number and PM10 show similar concentrations in both sites. Looking in more detail, NOx concentrations at the street site are almost a factor of three higher than in at the urban site during daytime. During nighttime, however, the concentrations at the urban site are somewhat higher than at the city site. These differences were to be expected since the City site is located on a busy street. This means that during daytime, when road traffic emissions are high, they will have a larger impact on levels at the City site than at Las Encinas that is located far from main roads. This is also evident during Sundays but with much lower concentrations both at the City and at Las Encinas.

However, the rather large difference observed between NOx at Las Encinas and at the City is not observed for other parameters. In fact, for BC we observe that the concentrations at the City are only about 50% larger than those measured in Las Encinas. Furthermore, particle number concentrations measured at both sites are rather similar throughout the day, except during the early hours of the night. PM10 concentrations measured at the City are also very close to those measured at Las Encinas.

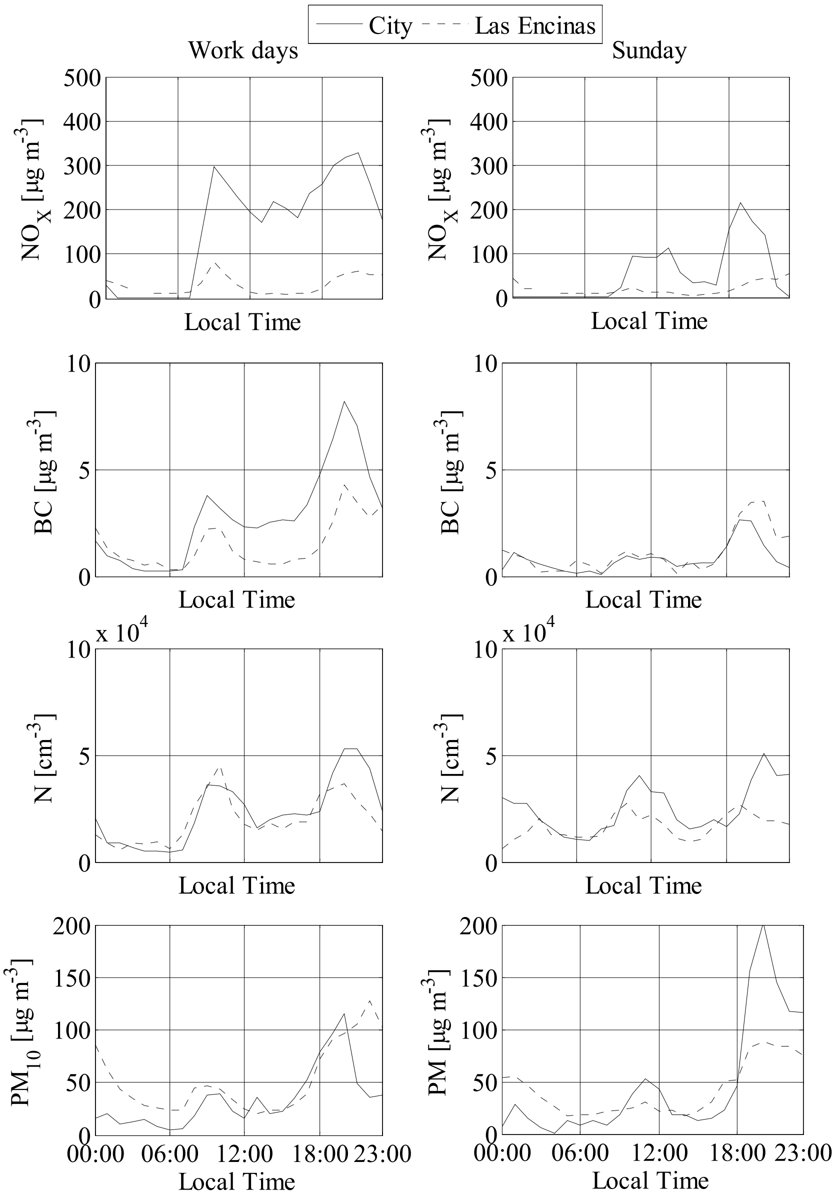


Figure 14. Diurnal cycle for weekdays and Sundays of the measured parameters in the City site canyon and at the urban station of Las Encinas. The left panels correspond to the week day variation and the right panel to the Sunday variation. As indicated in the figure, the first panels correspond to NOx, the second to black carbon (BC), the third to particle number concentration (N25-500 for the City and N10 for Las Encinas) and the last panels correspond to the PM10 concentration.

Considering that, as shown before, the City and Las Encinas sites are representative of the impact of different sources, namely traffic and wood combustion, the similar particle number concentrations are expected to be related to different size fractions. Figure 15 shows the average particle number size distribution for daytime (07:00 – 20:00) and nighttime (20:01 – 06:59) at the two sites and the diurnal variation of the particle number concentration for nucleation (25nm< Dp<50nm) and aitken (50nm < Dp < 150nm) modes.

Nucleation mode particles show higher concentrations in the City during daytime, which is consistent with the NOx/BC measurements that indicate that the City site is more affected by traffic emissions than Las Encinas. Aitken mode particles show a similar diurnal variation at both sites, except during the morning (09:00) when the concentrations at Las Encinas are usually higher than at the City. This may indicate that wood combustion emissions are associated with particle sizes around 100nm while traffic sources with particles smaller than 50nm. Particles larger than 200nm show no relevant differences between the two sites, which suggests that accumulation mode particles (Dp>200nm) are part of the background and may be related to long range transport and secondary aerosols.

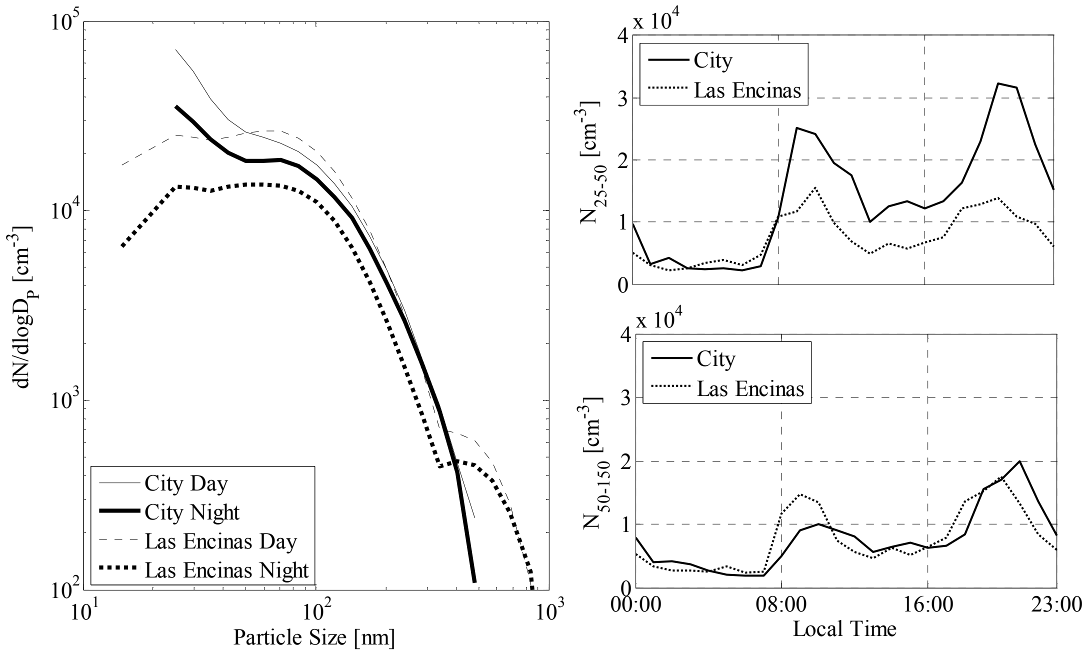


Figure 15. Diurnal variation of the particle number size distribution measured at the street and at the urban site. The left panel shows the particle number size distribution averaged for daytime (07:00 – 20:00) and nighttime (20:01 – 06:59). The dashed lines correspond to Las Encinas and the solid lines to the City. The heavy lines indicate daytime values and the thin lines indicate nighttime values. The right panel shows the diurnal variation of Nucleation mode (N25-50) and Aitken (N50-150).

7.2.1 Emission factors for road traffic and wood burning in Temuco

As indicated before, to estimate the emission factors from wood burning we compared the measurements at Las Encinas with the results from the Gaussian model. The emission factors from traffic, however, were estimated using the OSPM model and the measurements at the City station. Table 3 shows the obtained emission factors for PM10, NOx, BC, N10 and N25-600. Values reported in the literature are also shown for comparison.

Table 3. Comparison of particle number, NOx, black carbon emission factors estimated in this work with those obtained in previous studies. The total fleet emission factor was calculated considering 10% HDV for the lowest and highest estimate for HDV and LDV for each study. The uncertainty ranges in this study are given for the 95% confidence interval of the estimated emission factors.

Parameter	*Instrument*	*Site*	*Traffic (10% HDV) [mg ve^{-1} km^{-1}]*	*Wood burning [mg kg^{-1}]*	*Reference*
PM_{10}	Beta Gauge	Urban	--	1660±150	This study
PM_{10}	Optic	Street	610±51[3]	--	This study
$PM_{2.5}$	Gravimetry	Stack	--	7000 – 30000	Larson and Koenig, 1993
$PM_{0.9}$	TEOM	Stack	--	1300	Hedberg et al., 2002
$PM_{2.5}$	Optic	Tunnel	580[4]	--	Jamriska et al., 2004
PM_{10}	Beta Gauge	Street	72	--	Imhof et al., 2005
NOx	Chemilum.	Street/Urban.	4400±100	513±9	This study
	Chemilum	Chasis Dyn.	2000	--	Corvalan et al, 2002
	Chemilum.	Stack.	--	200 – 900	Larson and Koenig, 1993
BC	PSAP	Street/Urban	60±3	57±8	This study
	Aethalometer	Street	34	--	Imhof et al., 2005
	Various	Various	HDV no control: 160 – 525 HDV controlled: 32 – 64 LDV diesel no control: 60 – 300 LDV gasoline: 2 - 7	--	Kupiainen and Klimont, 2004
	Thermal	Stack	--	300 – 5000	Larson and Koenig, 1993
	PSAP	Street	71	--	Olivares et al., 2007a
			$*10^{14}$ [ve^{-1} km^{-1}]	*$*10^{14}$[kg^{-1}]*	
N_{10}	CPC	Urban	--	2.0±1.3	This study
$N_{25\text{-}600}$	DMA	Street/Urban	6.7±0.5	2.2±0.6	This study
$N_{3\text{-}850}$	DMA	Stack	--	3.8	Hedberg et al., 2002
$N_{16\text{-}400}$	DMA	Street	3.7	--	Olivares et al., 2007a
N_{10}	CPC	Tunnel	10	--	Gidhagen et al, 2003a
N_{10}	CPC	Tunnel	3	--	Kirchstetter et al., 1999[5]

[3] Estimates based on only one week of data.

[4] Emission factor reported for diesel buses

[5] Emission factors reported in a fuel basis were converted to veh-km^{-1} with a fuel economy of 10 km l^{-1} for LDV and 2 km l^{-1} for HDV.

Wood Burning

The emission factors estimated here are, generally, within the range of reported values from different sources. There are large differences in the methods used to obtain the emission factors. Hedberg et al (2002) as well as Larson and Koenig (1993) measured the parameters directly in the stack of a stove and related them to the wood consumption of the stove. Our estimates are based on ambient measurements and thus represent an average of several different types of appliances operated under different conditions. Because of this difference, direct comparison with laboratory results is not expected to give the same values.

Figure 16 shows our estimates for the size distribution of the particle number emission factors for wood burning. Considering the variability of the emission factors found in the literature, our results are within the reported emission factors found in the literature. Note that the emission factor seems to show a mono-modal distribution with a mode around 80nm. This mode is consistent with the results presented by Hedberg et al (2002). This indicates that traffic exhaust and residential wood burning emissions have different particle size distributions and that they can be qualitatively identified with the information gathered in this campaign.

Note that the small mode around 400 nm seems to be product of the different instruments used in the measurements, a DMPS between 20nm and 400nm and an OPC above 400nm.

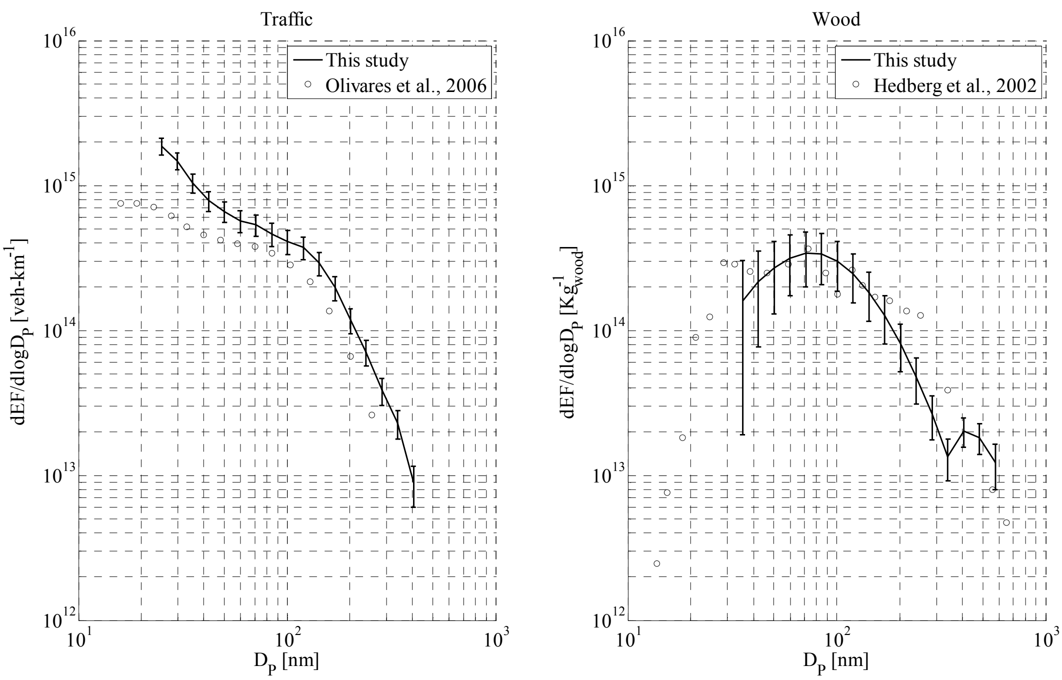


Figure 16. Size distribution of the obtained emission factors for Traffic [veh-km-1](left) and Wood burning [kg-1] (right). Results from Olivares et al (2007b) and Hedberg et al (2002) are shown for comparison (circles). The error bars indicate the 95% confidence interval for the emission factor estimates in this study.

Road traffic

Considering the variability in the reported emission factors, the estimates obtained here are consistent with the results previously reported in the literature (Olivares et al., 2007a; Corvalan et al., 2002). However, differences are noticeable for NOx and PM10.

The largest difference is observed for NOx, where our estimate is a factor of two higher than the reported by Corvalan et al. (2002) for Chilean vehicles. This difference may be related to the age of the Temuco fleet and the uncertainty in the HDV/LDV fraction. In fact, the vehicle fleet in Temuco is partially composed of used vehicles sold from the central part of Chile. This is particularly evident for the urban buses. The bus fleet in Temuco includes a large percentage of used vehicles from Santiago, where Corvalan et al (2002) measurements were made.

For PM10, our estimate is also higher than the literature values but comparable to the factors reported for diesel vehicles (Jamriska et al., 2004). In this case, the difference may be related to the fact that our method does not differentiate between tailpipe and road dust emissions. Therefore, they are expected to be higher than only tailpipe emission factors.

According to a literature survey by Kupiainen and Klimont (2004) BC accounts for between 22% and 70% of diesel exhaust particle emissions and between 5% and 30% of gasoline exhaust particle emissions. As can be seen in Table 3 BC emission factors for diesel exhaust is much higher than for gasoline. Uncontrolled HDV vehicles may emit 100 times more than gasoline vehicles.

7.3 Conclusions from measurements

The results show that Temuco's air quality is greatly affected by residential wood burning. Comparing the measurements of PM10, BC, NOx and N with model results, we have estimated the emission factors for residential wood combustion and also for the traffic fleet of the city. The emission factors obtained with this approach are representative of an average of the wood combustion sources and an average of the vehicle fleet in the area. Furthermore, the particulate emission factors do not differentiate between tailpipe and non-tailpipe emissions.

The size distribution of the particle number emission factor for traffic and wood combustion sources show different shapes. For traffic sources the size distribution suggests a bimodal shape with a primary mode below 50nm in diameter and a secondary mode above 100nm. For wood combustion there seems to be only a primary mode around 80nm. The features observed in the emission factor size distribution are consistent with results reported in the literature.

The uncertainty of the emission factor obtained here is relatively large. However, our results seem to be comparable with previous studies. The observed differences may be related to the average character of our emission factors, compared to those obtained from direct tailpipe or stack measurements. Shortcomings on the vehicle fleet composition and wood consumption information further add to the uncertainties of our emission factor results.

Using the obtained emission factors estimated the horizontal distribution of NOx and BC. The results indicated that the measuring sites were, as expected, mainly affected by different sources, further supporting their use to estimate the emission factors for the two emission sources.

7.4 Modelling of emissions in Temuco

The principal aim of this project was to provide a detailed characterisation of the aerosol in Temuco, so that conclusions concerning sources and dispersion pathways can be drawn. To achieve this air quality dispersion model calculations are an important complement to the size distribution measurements.

The objective of the model exercise is to support the interpretation of the aerosol measurements (mainly PM10 mass and size distribution) in terms of sources and their relative importance. More specifically:

- Describe the spatial distribution of PM emissions from traffic and wood burnning, as well as their temporal variation
- By comparing model results with measurements, conclude about the effective emissions from those two dominating sources.

Another important source for atmospheric PM is the burning of vegetation from agriculture activities. However, this source is active only during a very limited period which does not coincide with the critical wintertime periods of severe pollution. Vegetation fires will thus not be included in the model study. The model simulations have been implemented on the SMHI Airviro server, but the intention is that an identical implementation will be made on the CONAMA Airviro server administrated by DICTUC. This will allow CONAMA IX región to continue to work with the databases and the Gaussian model.

Two types of models were used in this work. An urban-scale Gaussian model for the wood related emission factors and a Street-canyon model for the traffic related emissions. Both models were used in a similar way to estimate the emission factors: The emission factors were adjusted to minimize the difference between the modelled and measured time series.

7.4.1 Description of the models used in Temuco

7.4.1.1 Gaussian model

The Gaussian model used in this work corresponds to the implementation included in the air quality management system AIRVIRO (www.indic-airviro.smhi.se). This model requires meteorological information for at least one site in the area. The information was provided by CENMA for two sites in the Temuco: Las Encinas and Padre Las Casas. The wind field calculation in the model is based on the concept first described by Danard (1977). This concept assumes that small-scale winds can be seen as local adaptation of large scale winds due to local fluxes of heat and momentum from the surface. Danard also assumes that horizontal processes can be described by non-linear equations while the vertical processes can be parameterized as linear functions (SMHI, 2004).

7.4.1.2 Street-canyon model

For the traffic related emission factors, the OSPM model was used (Berkowicz, 2000). The OSPM model is based on parameterizations describing the relationship between the emissions and the concentrations in the canyon. The model requires information about the geometry of the street, the traffic flow during the day and the wind above the buildings. The geometry of the street was obtained by exploration and measurements of the size of the buildings in the street. The traffic flow information used was the diurnal variation of the traffic flow reported for Temuco (CONAMA, 2002), adjusted and corrected with manual counts during the measuring campaign. The wind speed and direction was obtained from the information used for the Gaussian model.

7.4.2 Model input data

7.4.2.1 Meteorological data

CENMA has provided SMHI with hourly meteorological data from Las Encinas and Padre Las Casas. The 10 m wind direction and velocity at both places, as well as the temperature, have been used as input to two “principal meteorological stations” for the Airviro wind model. Standard deviation of the horizontal wind vector was given at Padre Las Casas, and has been used also at Las Encinas.

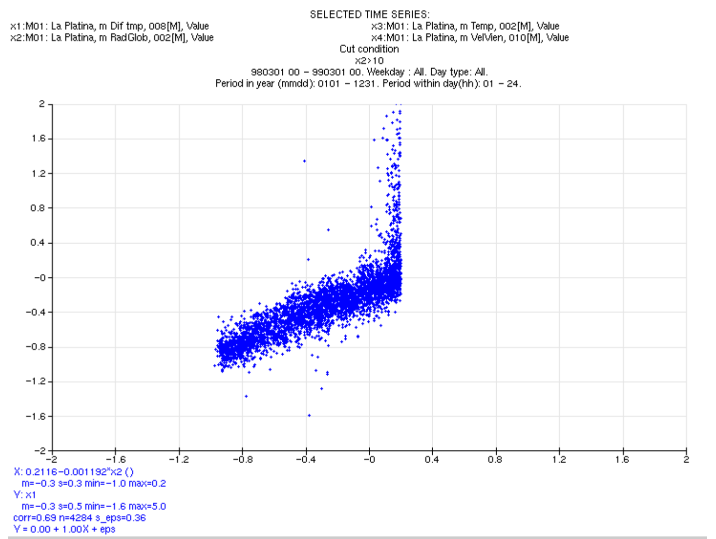
With respect to the requirements of the Airviro wind model, the major variable lacking in Temuco is the vertical gradient of ambient air temperature, normally measured as the temperature difference between 8 and 2 m. The variable is used to determine the heat flux and the resulting stability of the lowest surface layer. However, global radiation was measured at the Las Encinas station and a small study was performed to find relations between global radiation and temperature difference at a “similar” site, La Platina in Santiago.

The first relation was for global radiation > 10 W/m², i.e. daytime conditions with some sun radiation (Fig. 1). It can be seen that the negative difference normally observed during daytime conditions may be very nicely estimated from the global radiation value, through the relation:

$$\text{DiffT} = 0.2116 - 0.001192 * \text{Glob}$$

Fig. 1

Correlation between a regression modelled estimate (y-axis) of the temperature difference, based on global radiation, and the measured difference (x-axis).



For the cases where global radiation is below 10 W/m², which it is all nights, the problem to estimate the temperature difference is much more difficult. In Fig. 2 one can see a certain tendency to higher temperature differences with larger differences between temperature one hour ago and present temperature (cooling), this is seen as a linear slope in the right part of the left figure. However, large temperature differences are measured also during other phases of the day, even during heating conditions.

The right figure in Fig. 2 shows that large temperature differences occur for wind speeds below 2 ms^{-1}.

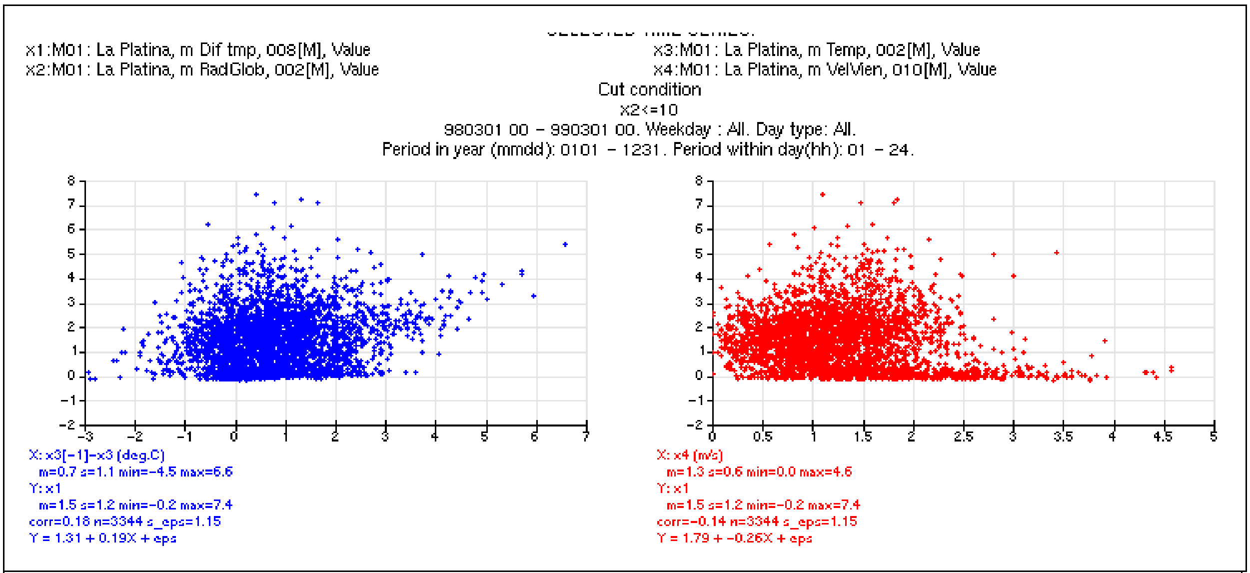


Fig. 2 Relation between temperature difference (y-axis) and temperature evolution during the last hour (x-axis left) and wind speed (x-axis right).

A model for temperature difference has been constructed based on the characteristics found at La Platina. The model covers four cases:

	Condition	*Difft =*
1	Glob > 10	0.2116 – 0.001192*Glob
2	Glob <10 & (Temp[-1h] – Temp) > 0.5	0.5706 + 0.6112*(Temp[-1h] – Temp) – 0.3611*Wspeed
3	Glob < 10 & Temp[-1h] – Temp) < 0.5 & Wspeed > 2	Constant value = -0.06
4	Glob < 10 & Temp[-1h] – Temp) < 0.5 & Wspeed < 2	Constant value = 0.5

An example of how the model performs in Santiago is given in Fig. 3. One could easily see that the model works well during the initial cooling (case 2), while the duration of the very stable conditions is interrupted to early. During daytime the performance is very good.

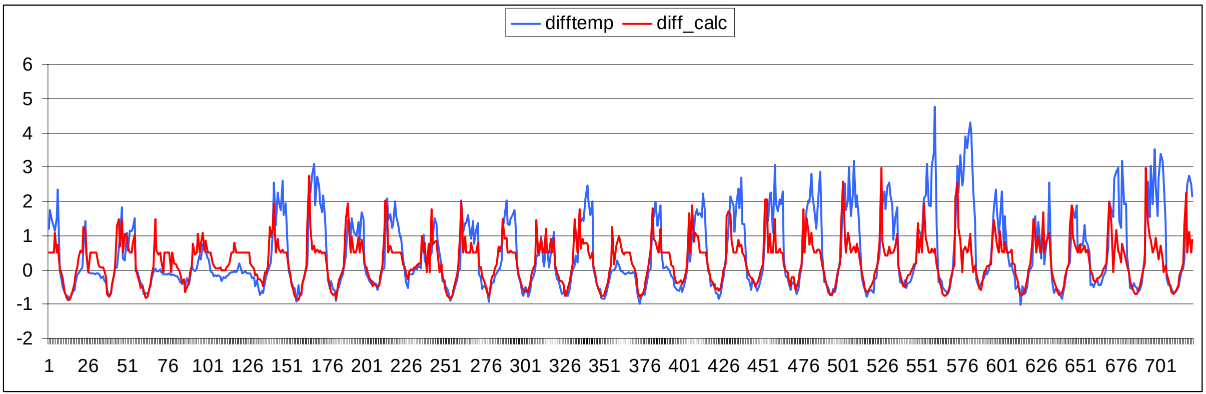


Fig. 3 Comparison of measured (blue) and model estimated temperature difference (red) at La Platina, Santiago. Period: March 1998.

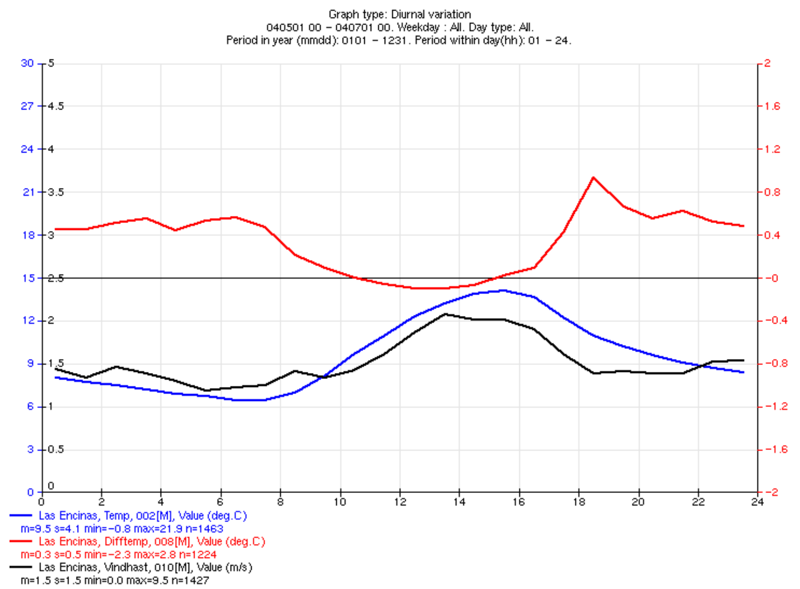
The model has been applied to global radiation, temperature and wind speed at Las Encinas. The same data has been used for the Padre Las Casas station. The average meteorological conditions are shown in Fig. 4. Note the very low wind speed.

Fig. 4

Daily variation at Las Encinans:

- Temperature (blue)
- Wind speed (black)
- Calculated temperature difference (red)

Period: May-Jun 2004



7.4.2.2 Emission data

The best available information from the Chilean Environmental Authority (CONAMA) contains data for mobile sources and residential wood burning. Industrial emissions were estimated to account for less than 2% of the total PM10 emissions during the fall-winter season (CONAMA, 2002).

The information about mobile sources consisted on total PM10 emissions for some 660 arcs that correspond to almost all the streets in the Temuco area (CONAMA, 2002). The original information differentiated between light and heavy duty vehicles, and between tailpipe and road emissions. However, this information was not available for this study. The available information included only annually averaged total PM10 emissions for each arc. The arcs were incorporated to the Airviro emission database system as ground level line sources and assigned diurnal variation according to the official information (CONAMA, 2002).

For residential wood burning, emissions were based on information on the annual wood consumption for the city. The information was divided originally in 12 areas according to administrative criteria. To implement this information in the Airviro emission database system, we first developed a map of the city where the residential areas were identified and differentiated from the streets and industrial and green areas. This was performed with aerial photography provided by the Chilean National System of Environmental Information (SINIA; http://siniav.conama.cl/fotografias_digitales_ix.php). With this map, we were able to distribute the wood consumption uniformly within each administrative sector only over the residential areas. Considering that the objective of this work is to estimate the emissions from residential combustion, only the wood consumption information was used.

To estimate the diurnal variation of the residential wood burning emissions, a test run of the Gaussian model was made. This run was done with an inert tracer with constant emissions during the day, distributed according to the wood consumption in Temuco. The results of this run were compared to the average diurnal variation of the PM10 concentrations measured at Las Encinas for the cold periods (T<10ºC) during the fall winter season of the year previous to the campaign (April – June 2004). The cold days were used to isolate the largest impact of wood burning. A diurnal variation of the emissions was then fitted to the model so they approximate the diurnal variation of the observed PM10 concentrations. The fitting was made with the concentrations, modelled and measured, normalized by their maximum value. In this way we have an estimate of the residential burning during fall-winter with a diurnal variation that reflects the operation in the city.

Existing information concerning traffic and wood burning emissions have been loaded into an Airviro emission database named *Tot2004*. The information gathered is older than 2004 (typically from 2001-2002), the name reflects the year used for a comparison between simulated and measured PM levels.

Road traffic

The most detailed and comprehensive information was found to be the Thesis work made by Lissette Flores, made in collaboration with CENMA. Lissette Flores was able to send to SMHI an EXCEL file with geographical coordinates and PM10 emissions for some 660 road links. She had worked with emission output from the MODEM emission model, thus it was not possible to get the traffic volume and vehicle fleet composition that once were used in the MODEM simulations. The implementation in the Airviro EDB has therefore been as follows:

- Road links, based on two pairs of coordinates, have been generated according to the Lissette EXCEL file.
- Instead of the number of vehicles on each road link, a value representing the emission in units of grams per meter and year is used.
- A single vehicle, with a constant emission factor of 2739 mg/km,veh, is connected to a sole roadtype (100% representation).

With this settings, the PM emissions will be properly distributed over Temuco and the total emission will be 1 229 tons/year (Figure 17). Temporal variations are taken from the final report "Inventarios de emisiones de contaminantes atmosférico en las regiones V, VI y IX de Chile", documento elaborated by CENMA. Figure 18 show the temporal variations used for all roads.

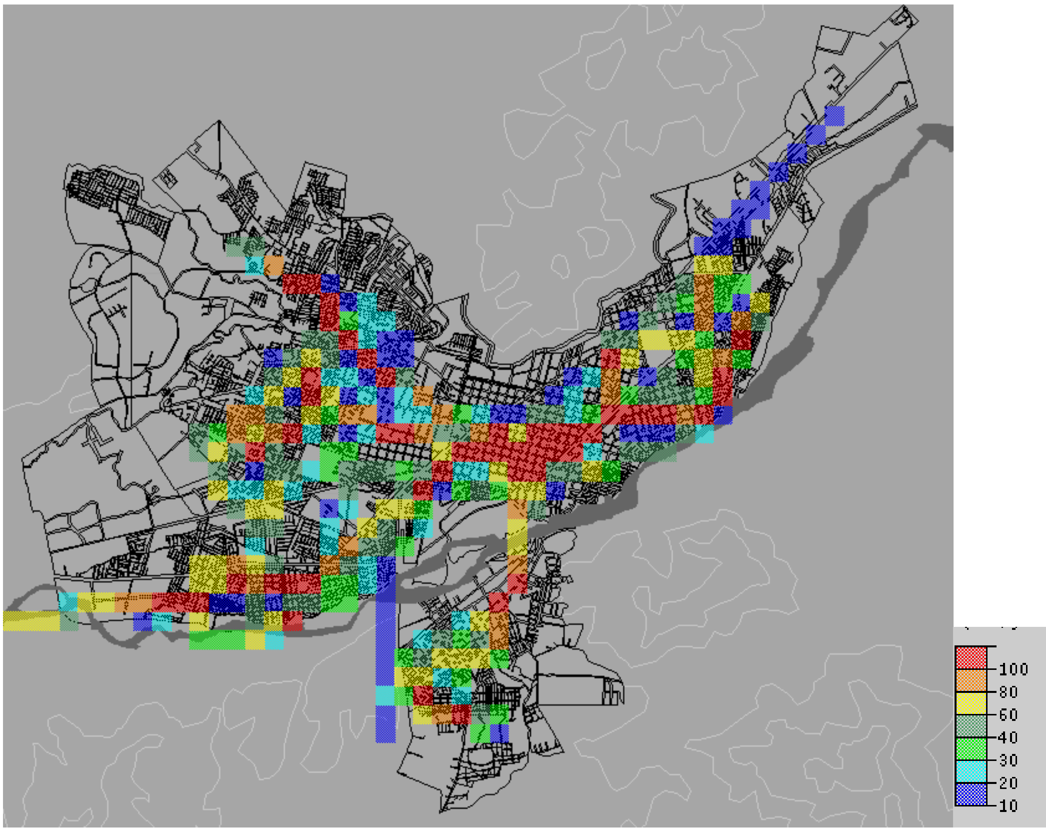


Figure 17. Distribution of traffic emissions (from Lissette Flores). Total PM emission: 1 229 tons/year.

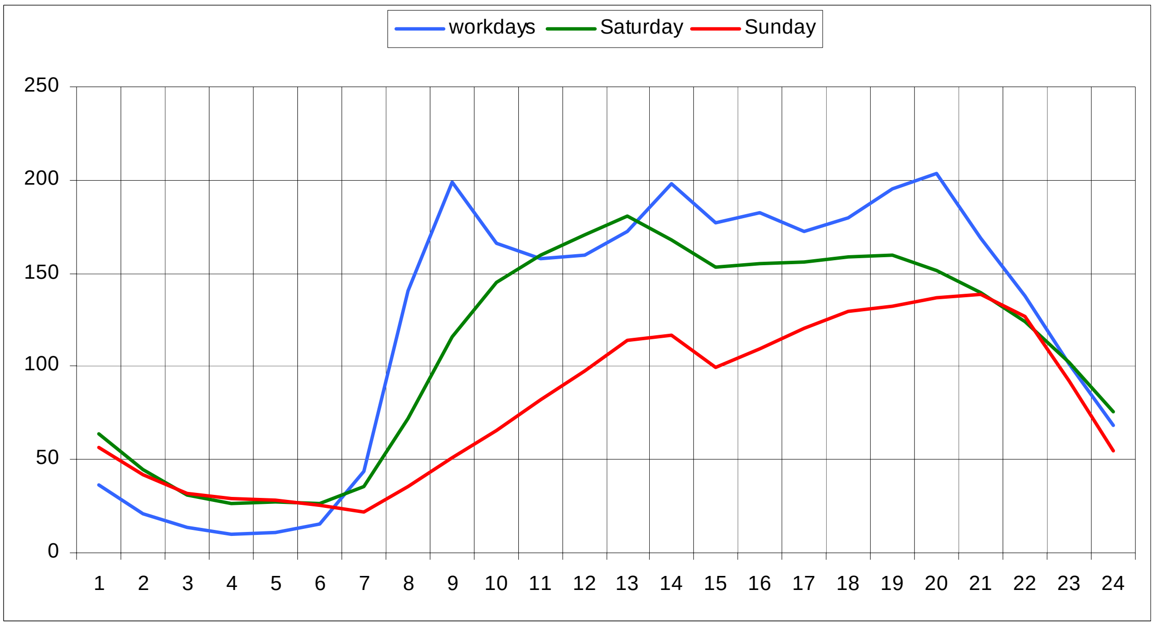


Figure 18. Temporal variations used for traffic volume (from CENMA).

Wood burning

The distribution of wood burning (consumption of wood for residential heating) was taken from the VITAE inquiry (obtained as shape files). The division into 12 districts is shown in Figure 19. The total wood consumption was estimated to be about 174 000 m^3 per year, with a separation between different districts according to Table 4. The extremely high wood consumption per unit area in Barrio Inglés (district 30) does not seem to be realistic and the value has been modified so that district 30 consumes wood at the same rate as district 2. This lowers annual wood consumption to about 163 000 m^3. The VITAE data is used as a base for the distribution of the PM10 emissions from wood burning.

The absolute values of the total PM10 emissions generated by residential wood burning in the 12 districts have been taken from the Executive Summary of the report "Elaboración del inventario de emisiones atmosféricas en la zona denominada Gran Concepción, document elaborated by CENM. There the emissions from residential wood burning are given as 2 281 tons of PM10 per year. With the modification of district 30, this value is reduced to 2 142 tons of PM10 per year (Table 4).

With standard data for the energy content (2200 kWh/m^3), the 2 142 tons of PM10 per year caused by the burning of 163 000 m^3/year translates to an average emission factor of 1660 mg/MJ. The emission factors used in the Swedish BHM project were between 22 mg/MJ for environmentally approved boilers with heat storage capacity to 2190 mg/MJ for old non-environmental boilers without any heat storage capacity. For stoves 110 mg/MJ was found in the Swedish study. The Temuco emission estimate is thus based on rather high emission factors, comparable to the highest Swedish factors for old boilers.

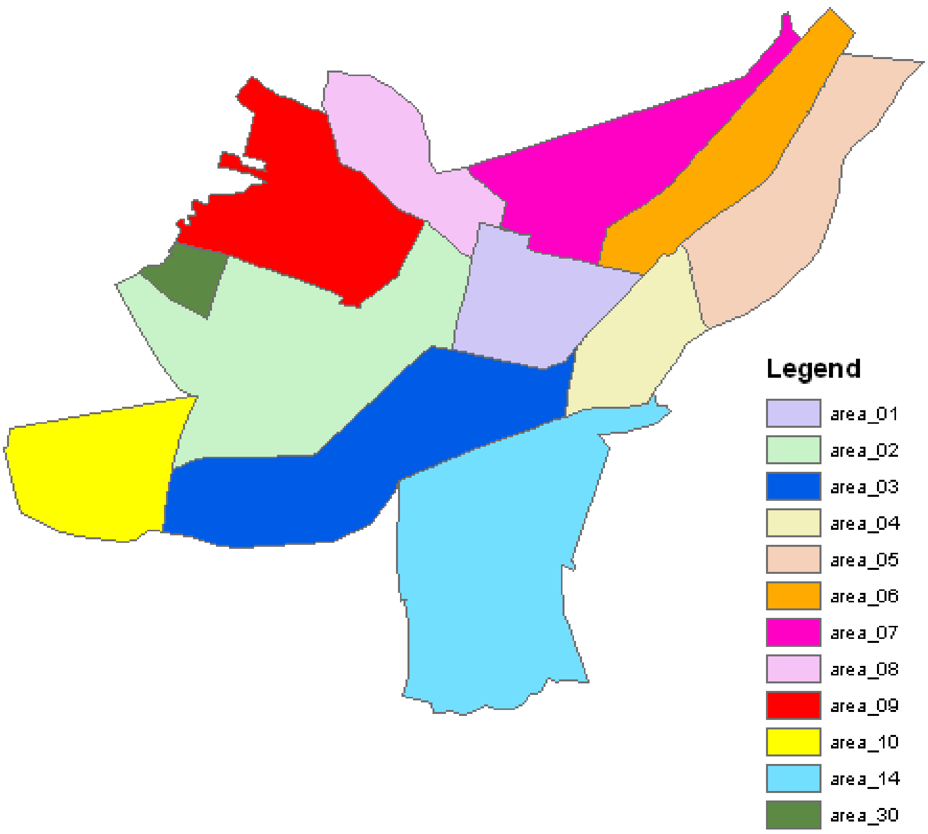


Figure 19. Distribution of wood burning emissions (from VITAE inquiry 2001)

Table 4. Distribution of wood burning emissions (from VITAE inquiry and CENMA).

	Annual consumption of wood for residential burning				
		(m3/year)	(250x250 m)		(ton/year)
N° of district	District	Total	number of cells	m3/cell	PM emission
1	Centro	5 505	37	149	72
2	Estadio Municipal	30 808	96	321	404
3	Amanecer	16 188	74	219	212
4	Santa Elena	5 982	27	222	78
5	Santa Rosa	18 777	49	383	246
6	Pueblo Nuevo	21 330	38	561	280
7	Ñielol	5 356	51	105	70
8	Lanìn	6 440	32	201	84
9	Av. Alemania	22 168	60	369	291
10	Labranza	6 706	42	160	88
14	Padre Las Casas	21 846	103	212	286
30	Barrio Inglés	12 843	7	1835	168
	Total general	**173 949**			**2 281**
30	Barrio Inglés (reduced)	2 246	7	321	29
	Total general (modified)	**163 353**			**2 142**

In the Airviro database, the wood burning emissions have been loaded on 250x250 m grid sources, one grid layer for each of districts. The input for each grid cell is the consumption of wood per year. The yearly average emission strength is displayed in Figure 20. The districts Pueblo Nuevo and Santa Rosa, in the eastern part of the city, are the those with the highest emissions from wood stoves.

No good data have been identified for describing the temporal variations of wood stove emissions. Sporadic observations made during the April visit indicated that the majority of the stoves were used mostly during evenings and nights. An inspection of the diurnal variability of PM10 levels at the monitoring sites Las Encinas and Padre Las Casas (Figure 21) show a temporal variability somewhat different from what is expected at traffic dominated environments (morning and afternoon peaks). Especially at Las Encinas the nighttime peak, expected from wood burning, comes out strongly, with small influence of the morning traffic peak hour. We conclude that the PM10 temporal variation at Las Encinas does reflect variations in wood burning, modified by dispersion conditions. A tentative temporal variation as in Figure 22, identical for all days of the week, has been used for the following model simulations.

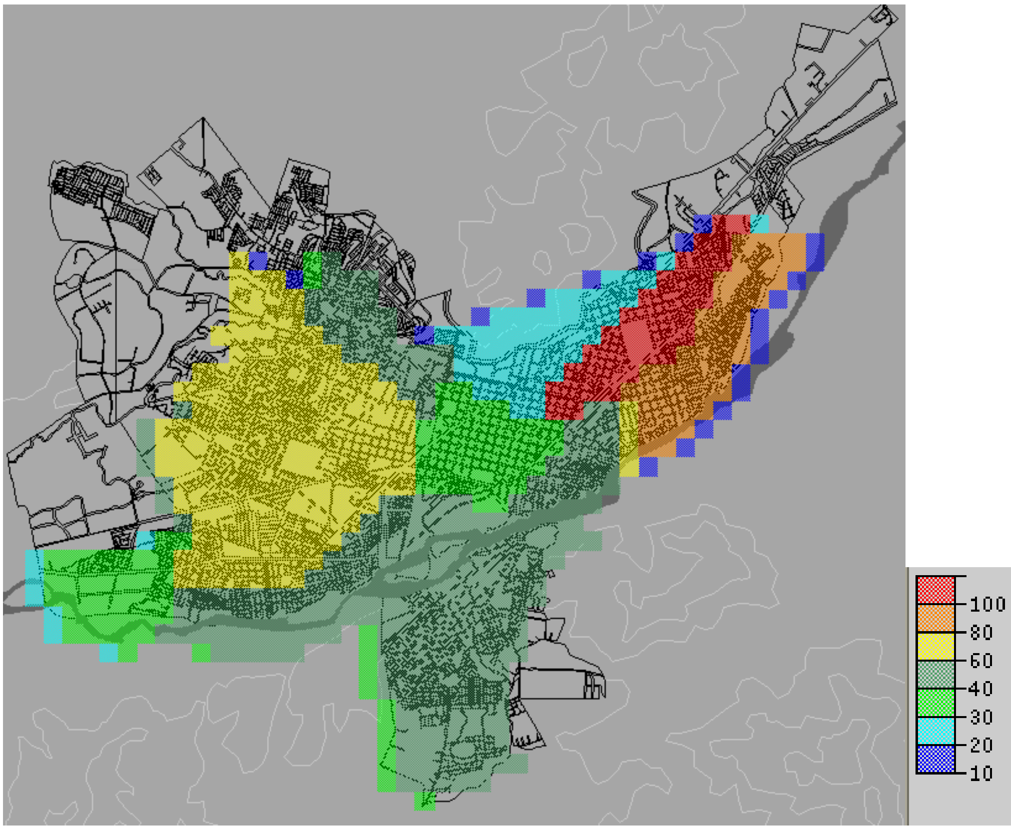


Figure 20. Distribution of wood burning emissions (from CENMA). Unit Tonnes/year.

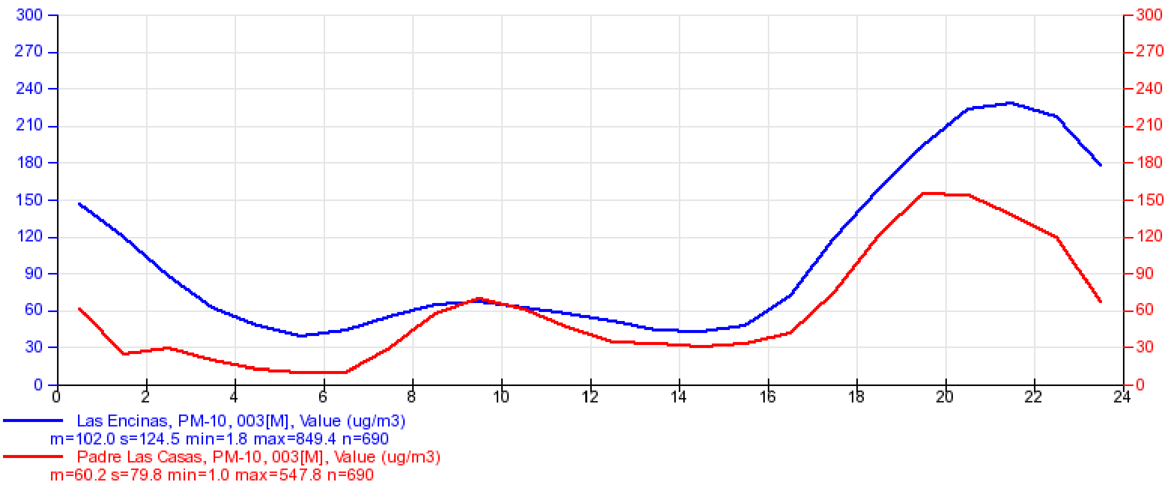


Figure 21. Daily variation of PM10 at Las Encinas (blue) and Padre Las Casas (red) (Workdays May-June 2004, arbitrary units).

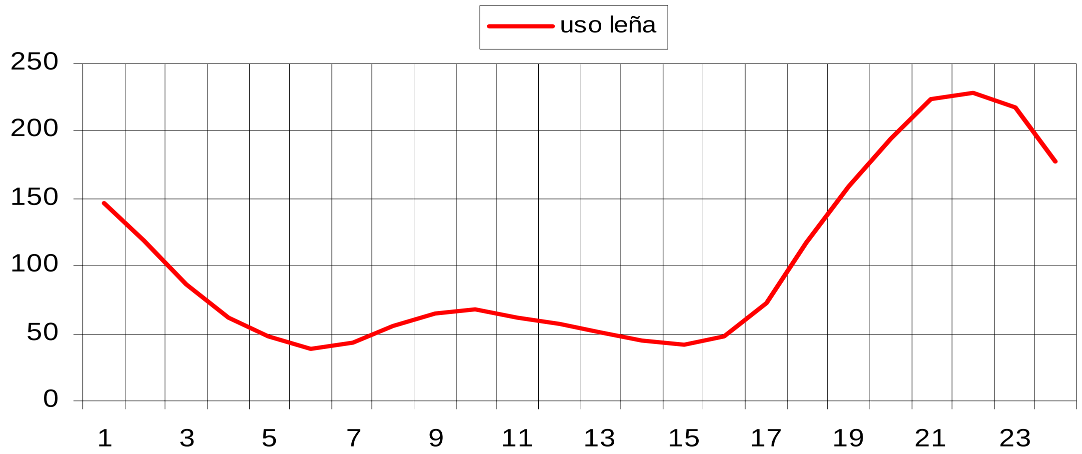


Figure 22. Daily variation of wood burning (estimated from the behaviour of PM10 levels at Las Encinas) (arbitrary units).

7.4.3 Results of simulations using the Gaussian model

We first present the results of a two months wintertime simulation, May-June 2004, in which the emission data have been used as presented above. In Figure 23 the daily variations (workdays only) of simulated PM10 concentrations at the two monitoring sites are compared to measured data. At both stations the simulated nighttime traffic and wood burning impact is higher than the measured levels, at Las Encinas the simulated levels are higher also during daytime.

If the comparison of simulated and measured PM10 concentrations at the two sites are representative for the entire city, then it is obvious that the estimated PM10 emissions are too high, the overestimation being roughly a factor of two. If the emission levels are to be compared to annual average emissions, this overestimation is even larger, as we are doing the comparison for two winter months during which wood burning is likely at its yearly maximum. Averaging over a year should contribute to even lower emission levels.

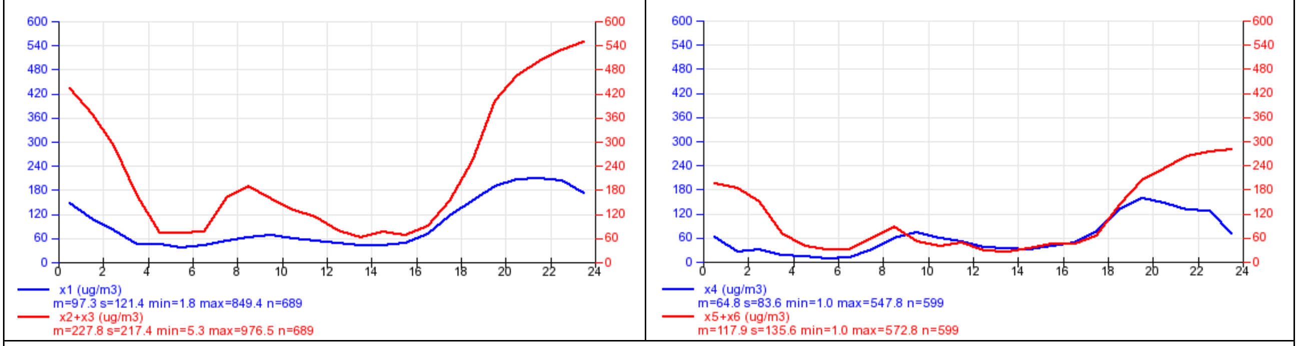


Figure 23. Daily variation during workdays at Las Encinanas (left) and Padre Las Casas (right). Meaured levels (blue) and simulated levels (red). Period: May-June 2004.

The distribution of the traffic impact on PM10 levels is concentrated to downtown (Figure 24) with PM10 levels from 100 μg/m³ to more than 180 μg/m³.

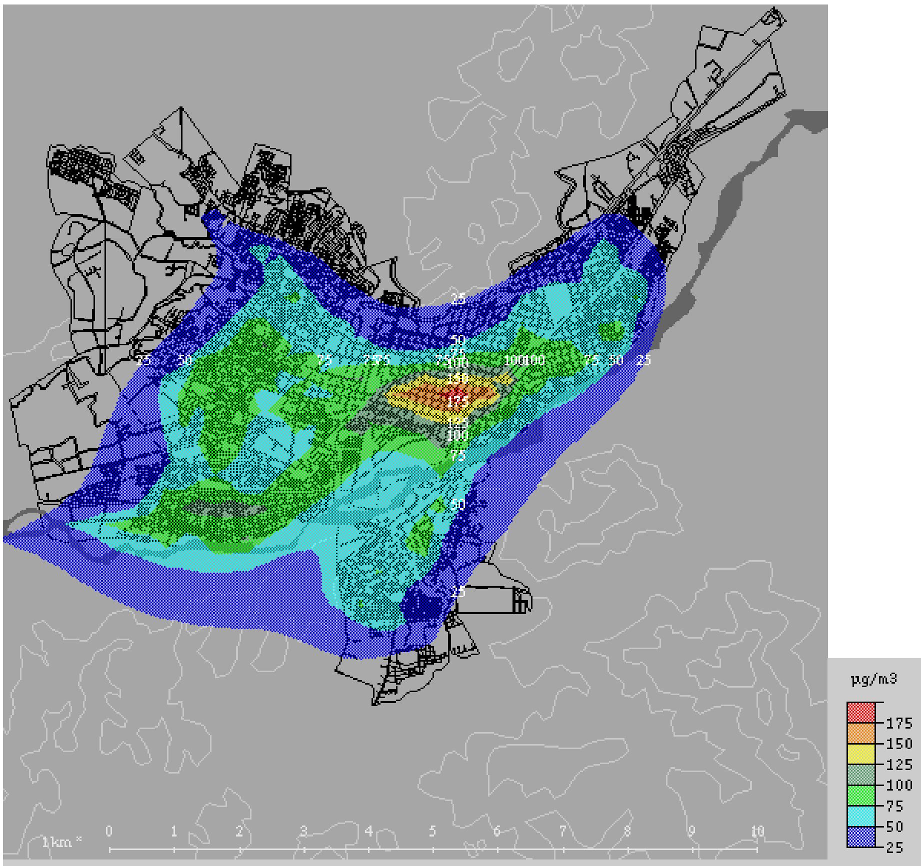


Figure 24. Annual average of PM10 levels as created by only traffic (emissions according to Figure 17). Period: May-Jun 2004.

The impact of the emissions from wood burning lead to somewhat lower maximum levels but is distributed over larger areas (Figure 25). In particular there are high levels in two areas, the northeast (Pueblo Nuevo, Santa Rosa) and in the west (Amanecer, Estadio Municipal, Av. Alemania, Barrio Inglés).

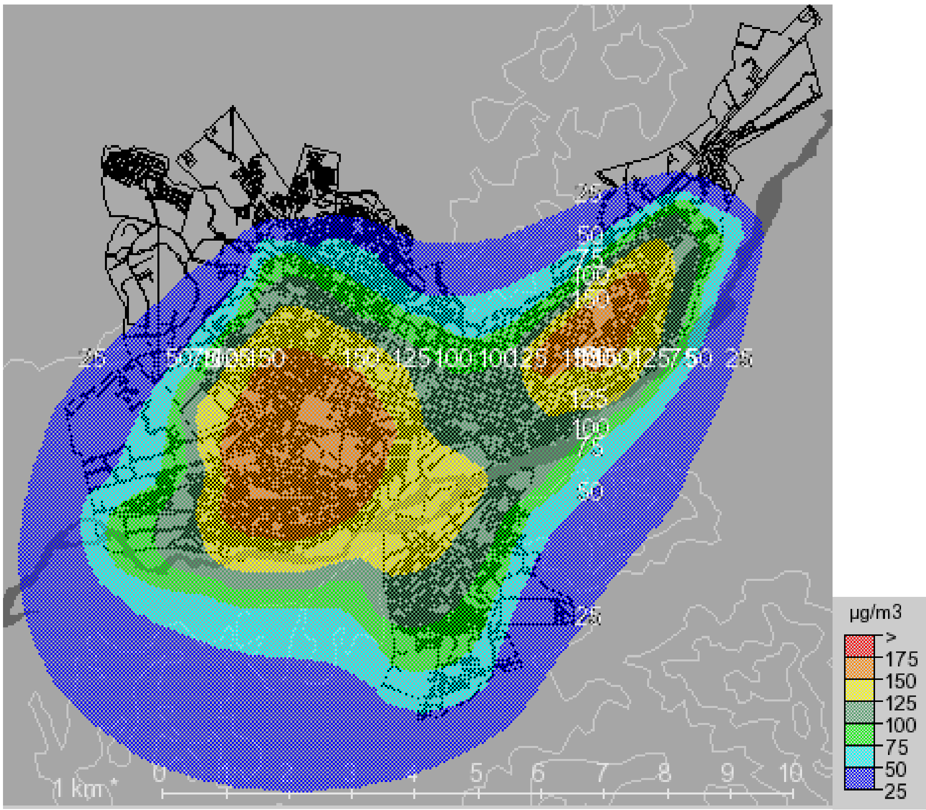


Figure 25. Annual average of PM10 levels as created by only wood burning (emissions according to Figure 20). Period: May-Jun 2004

7.4.3.1 Multiple regression analysis

The comparison shows that the impact on calculated levels due to the sum of traffic and wood burning emissions is higher than measured levels. It is therefore interesting to get a quantitative estimate of how large this overestimation is depending on traffic and wood stove sources, respectively. This is done by running a multiple regression analysis between the simulated impact and the measured PM10 levels at the Las Encinas and Padre Las Casas monitoring stations. The statistical program used for evaluation is the "MLRF F-criteria" of the Airviro system (Multiple linear stepwise regression based on forward selection).

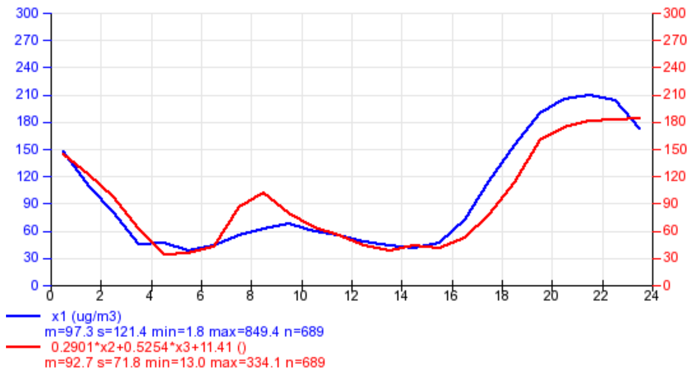
The results of the MLRF analysis is shown in Figure 26. What the MLRF tool does is that it analysis the time variations of the two simulated time series and try to combine them with an "amplitude factor" (B1 and B2) so that the error between the summed impact and the measured PM10 levels is minimized. A certain bias is always present, given as B0 by the MLRF tool.

The MLRF study confirms the earlier impression of more wood burning impact at Las Encinas and more traffic impact at Padre Las Casas. At Las Encinas the amplitude factor for wood burning (*B1*) is 0.29 and for traffic (*B2*) 0.52, the corresponding amplitude factors for Padre Las Casas are 0.22 and 1.00, respectively. The non-explained background part (*B0*) is 11-12 µg/m^3, which is reasonable.

With the amplitude factors and the bias of MLRF, the dispersion model output, in terms of the average daily variation, compares reasonably well with measured PM10 levels (lower diagrams of Figure 26).

Model size	1	2
Stdv (Y) (ug/m3)	116.5	116.5
Model error (RMSE)	97.81	93.49
Explained variation	29.49	35.57
Mult corr coeff (%)	54.3	59.64
B0	35.86	11.41
B1	0.3394	0.2901
Fv1	506.003	367.321
B2	---	0.5254
Fv2	---	115.306

Model size	1	2
Stdv (Y) (ug/m3)	80.46	80.46
Model error (RMSE)	64.71	60.85
Explained variation	35.32	42.81
Mult corr coeff (%)	59.43	65.43
B0	22.19	11.85
B1	---	0.2211
Fv1	---	139.782
B2	1.299	0.9988
Fv2	578.79	309.396



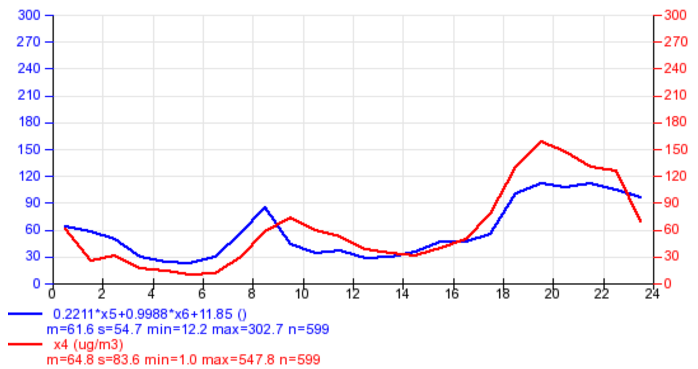


Figure 26. Left: Regression model for PM10 levels at Las Encinas. Daily variation during workdays, measured (blue) and regression model size 1 (red). Right: Regression model for PM10 levels at Padre Las Casas. Daily variation during workdays, measured (blue) and regression model size 2 (red).

7.4.4 Wood stove emissions and ambient temperature

In Figure 27 we have used the regression expression to simulate the PM10 levels at Las Encinas and Padre Las Casas. Although the simulated average daily variations (Figure 26) looked similar to the measured values, we can from Figure 27 see that the day to day peak variations during the two months long period is not well described by the model. Measured PM10 concentrations show high peak values during some days, while other days show comparatively low values.

The model variations are much more uniform from one day to another. Obviously there is something that is not well described by the dispersion model. We can speculate in either the emission variations or some processes not well captured by the dispersion model.

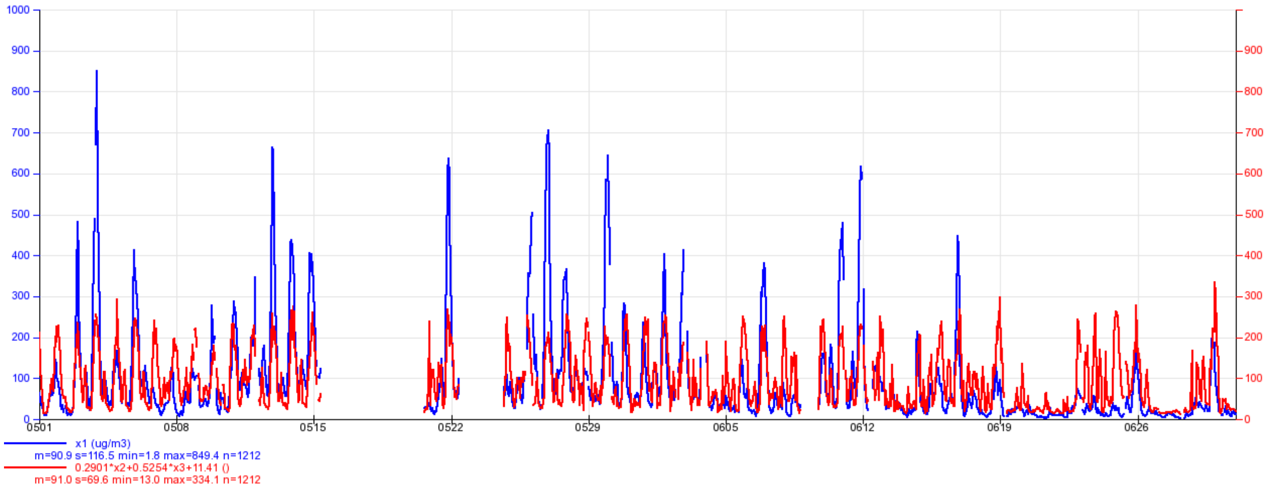


Figure 27. Hourly values of PM10 at Las Encinas: measured (blue) and regression model size 1 (red) May-June 2004

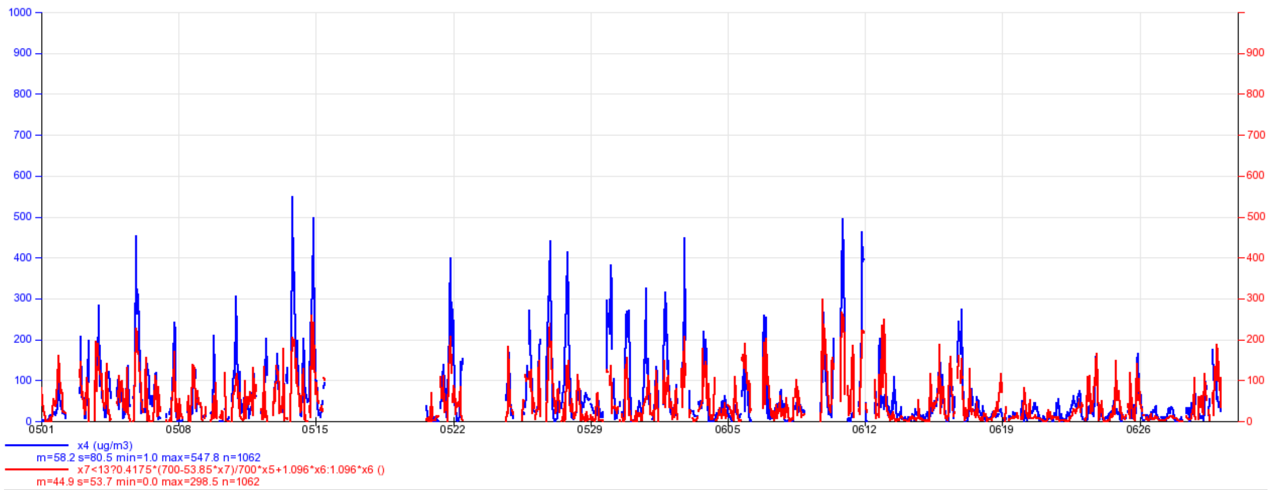


Figure 28. Hourly values of PM10 at Padre Las Casas: measured (blue) and regression model size 2 (red). May-June 2004.

There is one meteorological parameter - the temperature - that is likely to influence both the use of wood for heating purposes, as well as the dispersion conditions. During days with very low nighttime temperatures people will use more wood to heat their houses, this as compared to days with warmer nights. But strong cooling during the night is also a sign of strong inversions, which will cap the wood stove emissions from vertical dilution and contribute to high peak concentrations. The dispersion model should react on the latter, but as was shown above the stable, nighttime period is interrupted to early with the current parameterization of the vertical temperature gradient. In what follows, we will show that the temperature has information concerning the inversion strength.

As can bee seen from Fig. 15, the rate of cooling during three evening hours is correlated to high nighttime PM10 concentrations. This means that the high peaks of Figure 27 is likely to have occurred in nights when the temperature cooling was especially pronounced. We can use this at the top of the earlier regression model (Figure 26), which will put a higher amplitude of the daily variations during the evenings and nights with strong cooling. We will thus multiply the model output with *max((temp(-3 hours) – temp), 0).* The regression will then yield the coefficients of

Figure 30. The day to day variations of the simulated PM10 levels of Figure 31 show a much better similarity with measured variations.

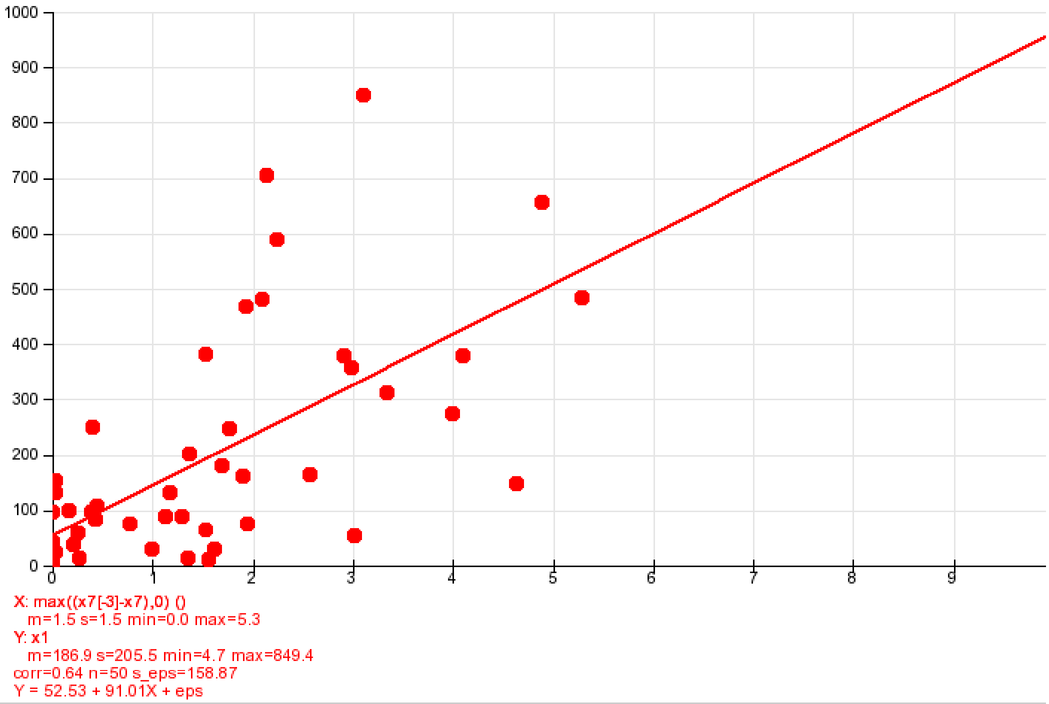


Figure 29. Hourly values of PM10 at Las Encinas at 23:00 hours as a function of the difference between the absolute difference in temperature between 23:00 and 20:00 hours (the magnitude of the temperature cooling during three evening hours). Period: May-June 2004.

Model size	1	2
Stdv (Y) (ug/m3)	116.5	116.5
Model error (RMSE)	82.12	80.38
Explained variation	50.33	52.42
Mult corr coeff (%)	70.95	72.4
B0	52.25	35.84
B1	0.1406	0.1289
Fv1	1225.22	924.531
B2	---	0.3175
Fv2	---	53.9265

Model size	1	2
Stdv (Y) (ug/m3)	80.46	80.46
Model error (RMSE)	58.42	53.85
Explained variation	47.28	55.21
Mult corr coeff (%)	68.76	74.3
B0	32.96	19.22
B1	0.1586	0.1198
Fv1	950.569	471.769
B2	---	0.7184
Fv2	---	188.711

Figure 30. Regression model for PM10 levels at Las Encinas (left) and Padre Las Casas (right) including the assumption of an enhanced impact of wood burning emissions during nights with strong cooling.

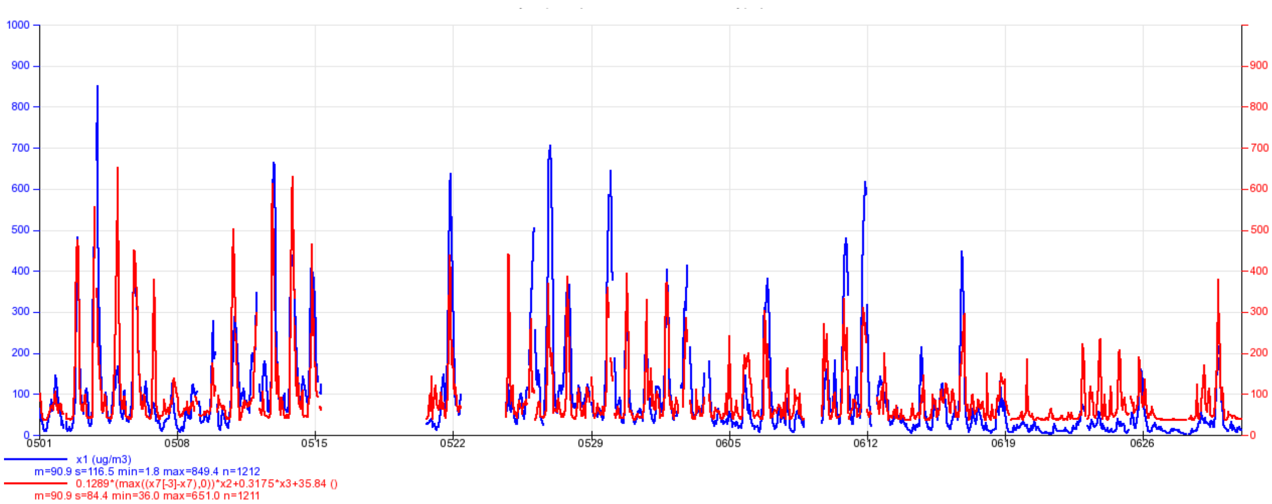


Figure 31. Hourly values of PM10 at Las Encinas: measured (blue) and regression model (red) including the effect of temperature cooling.

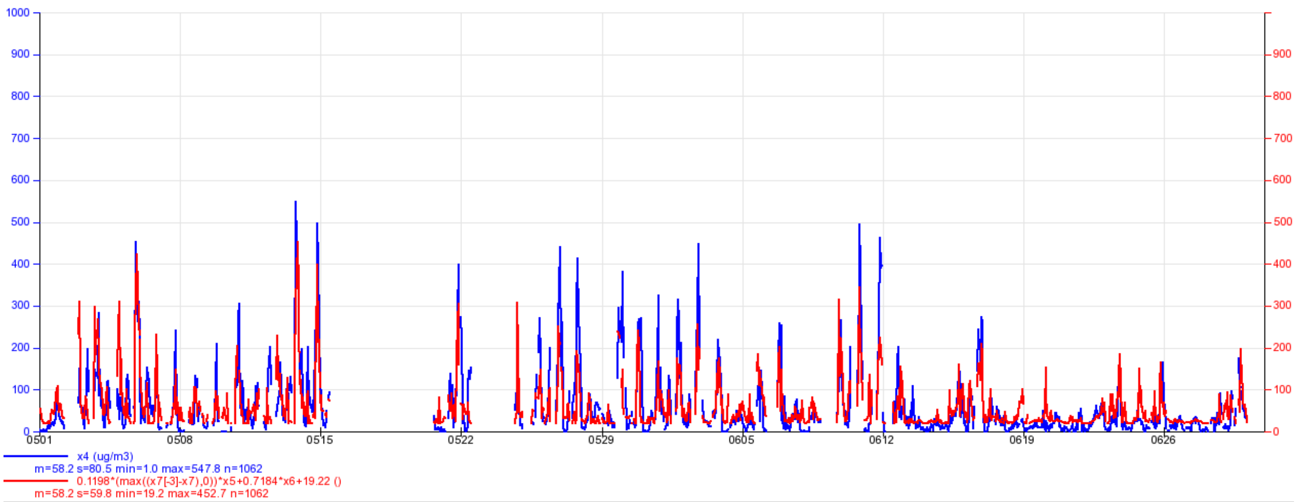


Figure 32. Hourly values of PM10 at Padre Las Casas: measured (blue) and regression model (red) including the effect of temperature cooling.

7.4.5 Conclusions and recommendations regarding modelling

With this first model study we have used air quality and meteorological data from 2004. We have also used emission data taken from historical studies. The comparisons between model simulations and measured data at two stations give the following conclusions:

- Traffic PM emissions with a total of 1 229 tons/year and distributed as indicated by the Lissette Flores thesis, give far too high impact at Las Encinas but reasonable levels at Padre Las Casas. This indicate errors in the spatial distribution, but does not allow us to conclude about the overall total.

- Wood stove emissions of the order of 2 200 tons/year seems to be far too high, even as an average emission level for the two winter months we have studied here. The model study indicate that the emission rate for those two months should be about 20% (PLC) and 30% (LE) of the 2 200 tons/year level. As an annual average this estimates should be considerably lower.

- The impact of wood stove emissions at Las Encinas show a day to day variability that correlates with the rate of temperature cooling during the evening and night. This may reflect both more intensive wood burning, i.e. higher emission rates, as well suppressed dilution due to strong inversions. Although the model setup is able to simulate reasonably the average daily variation, it does not respond to this day to day variability in a satisfactory way.

If this emission data base is to be used in future it need to be improved. Of high priority is to improve the knowledge of the emissions due to wood burning; checking the emission factors and the wood consumption. For the traffic source the important task is to improve the distribution of the roads in the emission data base. A "coordinate system" error may be found by analyzing the exact position of the Lissette Flores road links as compared to the digital map (Figure 33). It is also recommended that persons with local knowledge of the Temuco traffic pattern revise the position of streets with high emissions (red colour in Figure 33). There are also new roads that should be included in order to facilitate simulations valid for 2004 and 2005. For future use of the Airviro EDB it is important to introduce traffic volume (veh/day) at road link level, instead of the direct PM10 emissions as given in the Lissette Flores data set.

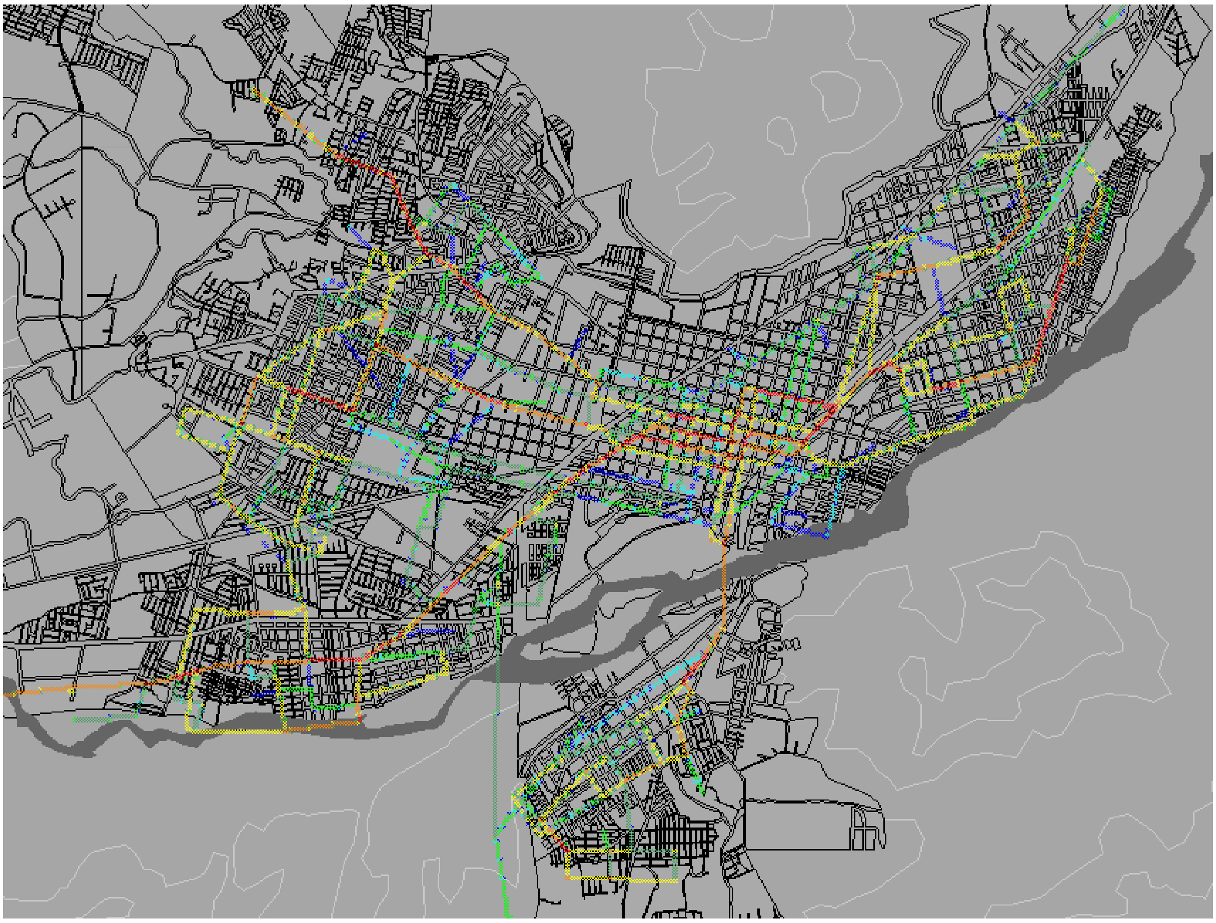


Figure 33. Distribution of traffic emissions according to the Lissette Flores data set.

For the wood stove source is also important to evaluate the geographical distribution of wood consumption as given by the VITAE study and listed in Table 4. The next uncertainty is to better describe the diurnal cycle, especially for the type of wood stoves that dominate the PM10 impact (small scale heating with emissions at low level, inside residential areas). It may also be possible to create a better geographical distribution than what is given by Figure 19, e.g. by overlaying residential areas and concentrate emissions to those areas. This will give zero wood stove emissions to non-populated areas, including traffic environments.

As stated before, the meteorological description (likely including data input) and the dispersion model should be improved to better respond to the nighttime inversions. Currently (2007), there is project in Sweden with the aim to develop a system for mapping of wood burning emissions in order to make more accurate dispersion modelling of the impact of wood burning on particle levels. The experiences gained from this activity might be useful also in future work in Temuco.

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9. References

Baik, J-J. and Kim, J-J. 1999. A Numerical Study of Flow and Pollutant Dispersion Characteristics in Urban Street Canyons. Journal of Applied Meteorology, 38, 1576 – 1589.

Berkowicz, R., 2000. OSPM – A Parameterized Street Pollution Model. Environmental Monitoring and Assessment, 65, 323 – 331.

Bogo, H., Otero, M., Castro, P., Azafrán, M.J., Kreiner, A., Calvo, E. and Negri, R.M., 2003. Study of atmospheric particulate matter in Buenos Aires city. Atmospheric Environment, 37, 1135 – 1147.

Celis, J., Morales, J., Zaror, C. and Inzunza, J., 2004. A study of the particulate matter PM_{10} composition in the atmosphere of Chillán, Chile. Chemosphere, 54, 541 – 550.

CENMA, 1999. Actualization of the Emission Inventory for the Metropolitan Region. Final Report for the National Comission for the Environment (Spanish). Available through CONAMA (www.conama.cl).

CONAMA, 1996. Mejoramiento de la información requerida para el control de la contaminación atmosférica en la Región Metropolitana, Final report, Junio 1996. Valentín Letelier 13, Santiago, Chile.

CONAMA, 1999. Revisión del plan de prevención y descontaminación atmosférica de la Región Metropolitana. Comisión Nacional del Medio Ambiente, Región Metropolitana de Santiago. Available at www.conama.cl. . Valentín Letelier 13, Santiago, Chile.

CONAMA, 2000. Área de trabajo 2: Dispersión regional de azufre oxidado en Chile Central usando el sistema HIRLAM-MATCH, Final report, Diciembre 2000. . Valentín Letelier 13, Santiago, Chile.

CONAMA, 2002. Prioritization of the air quality management measures to reduce the emissions due to residential wood burning in Temuco and Padre Las Casas (original in Spanish: Priorización de medidas de reducción de emisiones por uso residencial de leña para la gestión de la calidad del aire en Temuco y Padre Las Casas). Report prepared for the National Environmental Commission (CONAMA). Prepared by the University in Concepción, Chile. (http://www.sinia.cl/1292/article-28474.html Accessed: December 17th, 2006).

CONAMA, 2004. Continuity of the air quality and meteorology monitoring in Las Encinas station – Temuco. (original in Spanish: Continuidad de monitoreo de calidad de aire y meteorología estación Las Encinas de Temuco). Report prepared for the National Environmental Commmision (CONAMA). Prepared by the National Center for the Environment, Chile. (http://www.sinia.cl/1292/articles-28476_recurso_5.pdf Accessed: December 17th, 2006).

Corvalan, R., Osses, M. and Urrutia, C., 2002. Hot Emission Model for Mobile Sources: Application to the Metropolitan Region of the City of Santiago, Chile. Journal of the Air & Waste Management Association, 52, 167 – 174.

Danard, M. 1997. A simple model for mesoscale effects of topography on surface winds. Monthly Weather Review, 99, 831 – 839.

Gidhagen, L., C. Johansson, J. Langner and V. Foltescu, 2005. Urban scale modeling of particle number concentration in Stockholm. Atmospheric Environment, 39, 1711-1725.

Gidhagen, L., Johansson, C., Ström, J., Kristensson, A., Swietlicki, E., and Pirjola, L., 2003a. Model simulation of ultrafine particles inside a road tunnel. Atmospheric Environment, 37, 2023-2036.

Gidhagen, L., Johansson, C., Swietlicki, E. And Hansson, H.C., 2003b. Measurements of aerosol mass and size distribution in a residential area impacted by wood smoke. Presentation at the Particulate Matter: Atmospheric Sciences, Exposure and the fourth Colloquium on PM and Human Health March 31-April 4, 2003, Pittsburgh, PA, USA.

Gidhagen, L., Kahelin, H., Schmidt-Thomé, P. and Johansson, C., 2002. Anthropogenic and natural levels of arsenic in PM10 in Central and Northern Chile. Atmospheric Environment, 36, 3803-3817.

Hedberg, E., Kristensson, A., Ohlsson, M., Johansson, C., Johansson, P-Å., Swietlicki, E., Vesely, V., Wideqvist, U. And Westerholm, R., 2002. Chemical and physical characterization of emissions from birch wood combustion in a wood stove. Atmospheric Environment, 36, 4823 – 4837.

Imhof, D., Weingartner, E., Ordoñez, C., Gehrig, R., Hill, M., Buchmann, B. and Baltensperger, U. 2005. Real-World Emission Factors of Fine and Ultrafine Aerosol Particles for Different Traffic Situations in Switzerland. Environmental Science and Technology, 39, 8341-8350.

Ito A., and Penner, J., 2004. Global estimates of biomass burning emissions based on satellite imagery for the year 2000. Journal of Geophysical Research, 109, D14S05, doi:10.1029/2003JD004423.

Johansson, C., Wideqvist, U., Hedberg, E., Vesely, V., Swietlicki, E., Kristensson, A., Westerholm, R., Elswer, L., Johansson, P.Å., Burman, L., Pettersson, M., 2001. Cancerframkallande ämnen – Olika källors betydelse för spridningen och förekomsten i Stockholm. Institutet för tillämpad miljöforskning (ITM), Stockholms universitet, ITM rapport 90, ISSN 1103 341X.

Johansson, C., Norman, M. & Gidhagen, L., 2006. Spatial & temporal variations of PM10 and particle number concentrations in urban air. Environmental Monitoring and Assessment, DOI - 10.1007/s10661-006-9296-4.

Johnson, J.P., Kittelson, D.B. and Watts, W.F., 2005. Source apportionment of diesel and spark ignition exhaust aerosol using on-road data from the Minneapolis metropolitan area. Atmospheric Environment, 39, 2111–2121.

Kavouras I., Koutrakis P., Cereceda-Balic F., Oyola P., 2001. Source apportionment of PM10 and PM2,5 in five Chilean cities using factor analysis. J. Air & Waste Manage. Assoc. 51: 451 – 464.

Ketzel, M. and Berkowicz, R. 2005. Multi-plume aerosol dynamics and transport model for urban scale particle pollution. Atmospheric Environment, 39, 3407 – 3420.

Ketzel, M., Wåhlin, P., Berkowicz, R. and Palmgren , F., 2003. Particle and trace gas emission factors under urban driving conditions in Copenhagen based on street and roof-level observations. Atmospheric Environment, 37, 2735 – 2749.

Kirchstetter, T.W., Harley, R.A., Kreisberg, N.M., Stolzenburg, M.R., Hering, S.V., 1999. On-road measurement of fine particle and nitrogen oxide emissions from light- and heavy-duty motor vehicles. Atmospheric Environment 33, 2955–2968.

Kittelson D.B., Watts, W.F. and Johnson, J.P. 2006a. On-road and laboratory evaluation of combustion aerosols – Part 1: Summary of diesel engine results. Journal of Aerosol Science 37, 913 – 930.

Kittelson D.B., Watts, W.F. and Johnson, J.P. 2006b. On-road and laboratory evaluation of combustion aerosols – Part 2: Summary of spark ignition engine results. Journal of Aerosol Science 37, 931 – 949.

Krecl, P., Ström, J., & Johansson, C., 2007. Carbon content of atmospheric aerosols in a residential area during the wood combustion season in Sweden. Atmospheric Environment, 41, 6974-6985.

Kristensson, A., Johansson, C., Westerholm, R., Swietlicki, E., Gidhagen, L., Wideqvist, U. and Vesely, V., 2004. Real-world traffic emission factors of gases and particles measured in a road tunnel in Stockholm, Sweden. Atmospheric Environment, 38, 657-673.

Kupiainen, K. & Klimont, Z., 2004. Primary Emissions of Submicron and Carbonaceous Particles in Europe and the Potential for their Control. International Institute for Applied Systems Analysis (IASA), Interim report IR-04-79, Schlossplatz 1 A-2361 Laxenburg Austria.

Larson, T. and Koenig, J., 1993. Wood smoke: Emissions and noncancer respiratory effects. Annual Review of Public Health. 15, 133 – 156.

Ludwig, J., Marufu, L.T., Huber, B., Andreae, M.O., and Helas, G., 2003. Domestic combustion of biomass fuels in developing countries: A major source of atmospheric pollutants. Journal of Atmospheric Chemistry, 44, 23 – 37.

Marley, N., Gaffney, J., Baird, C., Blazer, C., Drayton, P. and Frederick, J., 2001. An empirical method for the determination of complex refractive index of size-fractionated atmospheric aerosols for radiative transfer calculations. Aerosol Science and Technology, 34, 535 – 549.

Martins, J., Artaxo, P., Liousse, C., Reid, J., Hobbs, P. and Kaufman, Y., 1998. Effects of black carbon content, particle size and mixing on light absorption by aerosols from bioimassburning in Brazil. Journal of Geophysical Research, 103, 32041 – 32050.

Miller, A., 1976. The climate of Chile. In: Schwerdtfeger, W., Landsberg, H.E. (Eds), World Survey of Climatology, Vol. 12. Elsevier Scientific Publishing Company, Amsterdam, pp 113 – 147.

Olivares, G., Gallardo, L., Langner, J., Aarhus, B., 2002. Regional dispersion of oxidized sulfur in Central Chile. Atmospheric Environment, 36, 3819-3828.

Olivares, G., Johansson, C., Ström, J. and Hansson, H-C., 2007a. The role of ambient temperature for particle number concentrations in a street canyon. Atmospheric Environment, 41, 2145-2155.

Olivares, G., Johansson, C., Ström, J., & Gidhagen L., 2005. Real-world particle number emission factors from residential wood burning. Presented at the European Aerosol Conference, Salzburg, Austria, Sept. 9-14, 2007 and at a conference in Temuco, Chile, 2005.

Olivares, G., Johansson, C., Ström, J., & Gidhagen L., 2007b. Black carbon and size resolved particle number emission factors estimates for residential wood burning. Submitted for publication in Atmospheric Environment.

Olivares, G., Johansson, C., Ström, J., Hansson, HC., & Gidhagen L., 2007c. Black carbon and size resolved particle number emission factors estimates in Santiago – Chile. Submitted for publication in Atmospheric Environment.

Olivares, G. (2005). Heavy duty diesel emissions and its impact on aerosol dynamics in street canyon conditions. in Proc. NOSA Aerosol Symposium 2005, Göteborg, Sweden, November 3-4.

Ostro B., Eskeland GS., Feyzioglu T. and Sanchez JM., 1999. Air Pollution and Health Effects: A Study of Medical Visits Among Children in Santiago, Chile. Environmental Health Perspectives 107: 69 – 73.

Ostro B., Sanchez JM., Aranda C., Eskeland GS., 1998. Air Pollution and mortality: results from a study of Santiago, Chile. J. Expos. Anal. Environ. Epidemiol. 6(1): 97 – 114.

Ostro, B., Broadwin, R., Green, S., Feng, W-Y and Lipsett, M. 2006. Fine Particulate Air Pollution and Mortality in Nine California Counties: Results from CALFINE. Environmental Health Perspectives, 144, 29 – 33.

Pino P., Oyarzún G., Walter TK., Von Baer D., Romieu I., 1998. Contaminación aérea intradomiciliaria en el área sur – oriente de Santiago. Rev Méd Chile. 126: 367 – 374.

Querol, X., Alastuey, A., Rodriguez, S., Plana, F., Ruiz, C., Cots, N., Massagué, G. and Puig, O., 2001. PM_{10} and $PM_{2.5}$ source apportionment in the Barcelona metropolitan area, Catalonia, Spain. Atmospheric Environment, 35, 6407 – 6419.

Reid, J. S., Hobbs, P. V., Liousse, C., Martins, J. V., Weiss, R. E. and Eck, T. F., 1998. Comparisons of techniques for measuring shortwave absorption and black carbon content of aerosols from biomass burning in Brazil. Journal of Geophysical Research Atmospheres, 103(D24), 32031–32040.

Rutllant, J. and Garreaud, R., 1995. Meteorological air pollution potential for Santiago, Chile: towards an objective episode forecasting. Environmental Monitoring and Assessment 34, 223 – 244.

Sharma, S., Brook, J.R., Cachier, H., Chow, J., Gaudenzi, A. and Lu1, G., 2002. Light absorption and thermal measurements of black carbon in different regions of Canada. Journal of Geophysical Research, 107 (D24) 4771.

Silva, C. and Quiroz, A. 2003. Optimization of the atmospheric pollution monitoring network at Santiago de Chile. Atmospheric Environment, 37, 2337 – 2345.

SMHI, 2004. Working with the dispersion module client. Swedish Meteorology and Hydrology Institute. (http://www.indic-airviro.smhi.se/Info/manual/3.11/Dispersion_Volume4_v3.11.pdf Accessed: January 2nd, 2007).

Tsapakis M., Evaggelia L.,Stephanou E., Kavouras I., Koutrakis P., Oyola P., von Baer D., 2002. The composition and sources of PM2,5 organic aerosol in two urban areas of Chile. Asmospheric Environment 36: 3851 – 3863.

Vardoulakis, S., Fisher, B., Pericleous, K. and Gonzalez-Flesca N, 2003. Modelling air quality in street canyons: a review. Atmospheric Environment 37, 155 – 182.

Weingartner, E., Keller, C., Stahel, W. A., Burtscher, H. and Baltensperger, U., 1997. Aerosol emission in a road tunnel. Atmospheric Environment, 31, 451–462.

Wiedensohler, A., 1988. An approximation of the bipolar charge distribution for particles in the submicron size range. Journal of Aerosol Science, 19, 387 – 389.

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