Estimating Social and economic benefits for natural gas use in transport and heating in Santiago, Chile using WRF-Chem.

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1. Introduction

Historically when fuels are compared only technical and economic aspects are considered in terms of comparisons of which is cheaper overall. However, this approach often overlooks differences in environmental impacts, externalities. Some of these can be quite large, sometimes doubling or tripling the direct cost of the fuel in the case of coal, or example (Epstein, Buonocore et al. 2011). Many of these externalities are related to increased health effects due to acute and chronic exposure to particulate matter, including increased mortality, respiratory symptoms, asthma attacks, among others (Dockery, Pope et al. 1993; Pope, Thun et al. 1995; Seaton, Macnee et al. 1995; Samet, Dominici et al. 2000). Chile has incorporated the social and economical evaluation of environmental regulations ever since their environmental institutions were created, as these are mandated to consider economic efficiency, using tools such as cost-benefit analysis (Ministry of the Environment 2007; Katz 2010). To meet these requirements methods were developed to estimate the economic impacts of these health benefits (Cifuentes and Lave 1993). Therefore cost benefit analysis is used for regulatory instruments such as air quality and emission standards, along with air quality attainment plans. These have evolved in sophistication starting from rollback methods coupled to factors that relate emissions with concentrations (Chang and Winstock 1975) which were used to support the Chilean PM2.5 (particulate matter of less than 2.5 um in aerodynamic diameter) air quality standard cost –benefit analysis(Cifuentes 2010). Also the newly approved Chilean power plant emissions standard included the coupling of an electric tariff model to project future emissions, with an atmospheric dispersion model to explicitly calculate benefits from reducing primary and secondary PM under regulatory scenarios (KAS 2009).

Santiago, Chile, has benefited from using cost-benefit analysis to support the measures in their pollution attainment plans. Since 1989 annual means of PM2.5 have been reduced from 69ug/m3 to 25ug/m3 in 2010, in a process that included the systematic reduction of emissions both through episodic and permanent air quality management strategies (Jorquera, Orrego et al. 2004), which have included banning wood burning and curtailing industrial emissions during bad air days, reduction of sulfur in fuels (30 ppm in diesel as of 2008), overhaul of public transportation system, and Euro IV emissions standards for new light vehicles. One of the most controversial measures was the Transantiago project (Yanez, Mansilla et al. 2010), which in 2007 came online with the objective to reduce redundant urban bus routes, and integrate these to Santiago's underground transportation system, the Metro. The environmental benefits of this project were set back (Valencia 2008) as the original plan intended to replace old Euro I buses with Euro III buses with particulate filters, but operational issues caused this overhaul to be incomplete. More buses were needed than the design value (5343 total buses) and the extra buses were revamped from the previous transportation system meeting less stringent Euro I and II emission standards. Also imports of natural gas from Argentina (used for residential and industrial applications) were curtailed starting 2004 forcing the use of dirtier liquid fuels for industry. It wasn't until late 2009 that natural gas supply was reestablished, when a liquefied natural gas terminal came online in Quintero(Azzopardi 2009). In 2010, with a full year of operation of the terminal, Santiago reached its lowest historical level of annual PM2.5. At the same time Movibus, Chile's first natural gas transportation system, was established in Punta Arenas. Since then there has been much discussion on whether increased use of natural gas in residential and transportation applications can replicate the success of emissions reductions in industrial sources.

This paper intends to evaluate what increased benefits can natural gas use in the transportation system and in residential heating, coupling an air quality model coupled to high resolution population density maps to evaluate seasonal variability of exposure, and finally the economic valuation of health benefits associated to this reduction. Figure 1 shows a generalized schematic of this approach, which involves calculating changes in emissions under different scenarios, how these emissions change ambient concentrations, and how these ambient concentrations affect exposure, which ultimately allows estimation of differences in health effects.

2. Methods

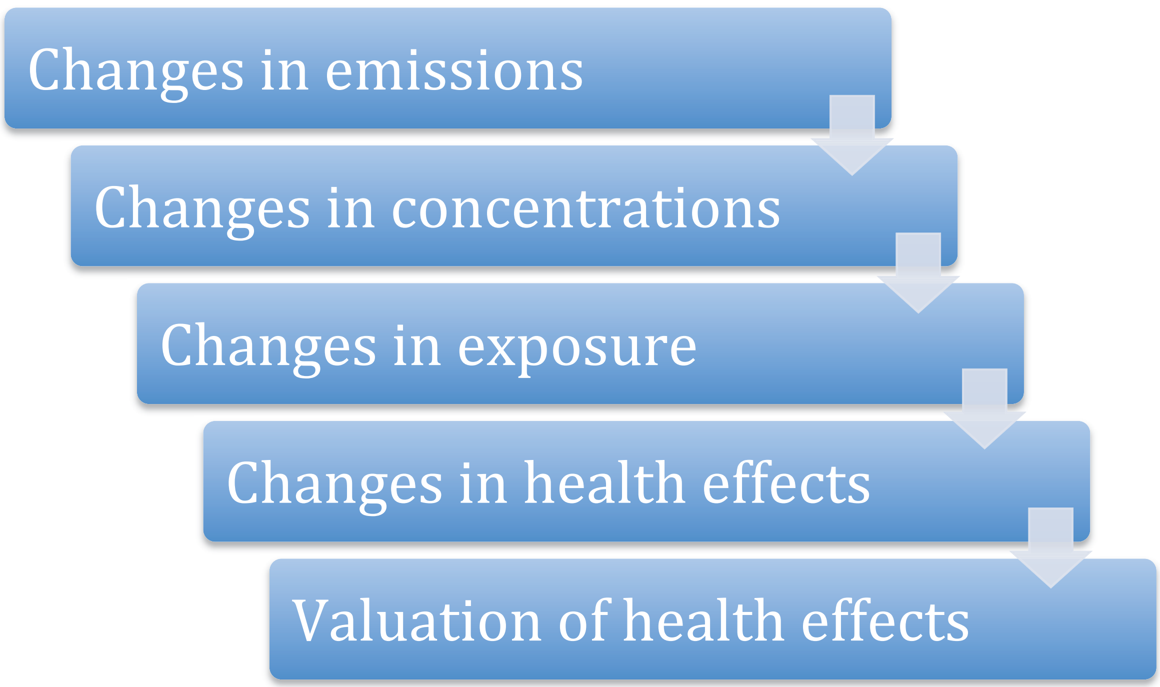
The basic method consists of estimating decreased exposure due to decreased emissions of PM, NOx, and SOx in two scenarios: implementing natural gas buses to replace current diesel buses, and implementing natural gas in replacement of the wood burning heaters, in Santiago, Chile.

1.1 Model

The WRF-Chem model (Weather Research Forecast, Chemistry) (Grell, Peckham et al. 2005) was used with 2 nested domains, of 12 and 4km resolution, respectively. The larger domain (267 by 178 grid cells) extends from Southern Perú to the Puerto Montt region, and incorporates the Pacific Ocean. The nested domain (97 by 98 grid cells) focuses Santiago and surrounding areas. The model treated gaseous species using the RACM scheme (regional atmostpheric chemistry model) (Stockwell, Kirchner et al.

1997) and GOCART (Georgia Tech/Goddard Global Ozone Chemistry Aerosol Radiation and Transport Model) (Ginoux, Chin et al. 2001) which has a simplified treatment of aerosol chemistry that but includes online sea salt and dust emissions driven by wind and secondary formation of sulfate from sulfur dioxide. GOCART is not as computationally intense as other aerosol schemes such as SORGAM (Secondary organic aerosol model)(Schell, Ackermann et al. 2001) or MOSAIC(Zaveri, Easter et al. 2008), and can reasonably used for longer simulations required for exposure applications, and was stable for the computational framework used (8 processors, 32 GB ram, Xeon processors).

Figure 1 Schematic of method to estimate benefits mobile and residential emissions scenarios.



1.2 Emissions.

This project used the VOCA emissions inventory (http://www.cgrer.uiowa.edu/VOCA_emis/) developed for the VOCALS aircraft measurement campaign (Bretherton, Wood et al. 2010). This inventory consolidated emissions inventories from air quality attainment plans and the power plant emissions standard cost-benefit study(KAS 2009). For Santiago the 2005 emissions inventory for PM10, PM2.5, CO, NOx, SO2, NH3, and volatile organic compounds for the industrial, residential, and transportation sectors, which are updated as described in the subsequent sections.

Table 1 shows the annual emissions for this inventory, which shows that carbon monoxide emissions are dominated by mobile sources, sulfur dioxide by industrial sources, and PM2.5 primary emissions are dominated by areal sources.

Table 1 Official emissions inventory for Santiago Metropolitan Area, Base Year 2005, tons/year

Sector	PM10	PM2.5	CO	NOx	COVs	SOx	NH3

Industry	1,267	994	7,745	12,332	7,542	12,829	217
Residential wood burning	693	674	8,235	85	7,466	12	71
Other residential heating	79	70	338	1,161	41,242	294	3,800
Commercial	0	0	0	0	7,911	0	0
Agricultural burning	247	235	2139	102	171	12	12
Other areal emissions	652	466	5249	136	18609	0	27725
Public Transportation	316	82	515	2507	235	9	1
Trucks	763	671	3515	11180	2199	44	7
Light duty vehicles	516	249	207,351	173,50	16,919	70	1,010
Off road	155	142	2,215	973	320	46	32
Total Mobile Sources	1,750	1144	213,596	32,010	19,673	169	1,050
Total Areal Sources	1,671	1,445	15,961	1484	75,399	318	31,608
Total Industrial Emissions	1,267	994	7,745	12,332	7,542	12,829	217
Total primary emissions	4,688	3,583	237,302	45,826	102,614	13,316	32,875

Table 2 shows a summary of all of the emissions inventories used. Sources outside of Chile were estimated based on EDGAR 3.2(Olivier, Bouwman et al. 1994) for gaseous species, and on the Bond (2004) global emissions inventory for black carbon and organic carbon. Regional inventories from mobile sources were taken from SECTRA, the Chilean Planning Office for Transportation.

Table 2 Summary of emissions inventories configurations.

Geographical Area	Sector	Inventory name	Species	Base Year
Metropolitan Region	Mobile Sources	SECTRA	PM10, PM2.5, CO, NOx, Sox, VOCs, NH3	2010
Metropolitan Region	Residential Sources	Chilean Ministry of environment(DICTUC 2007)	PM10, PM2.5, CO, NOX, SOX, VOC, NH3	2005
Metropolitan Region	Point Sources	Chilean Ministry of environment(DICTUC 2007)	PM10, PM2.5, CO, NOX, SOX, VOC, NH3	2005
Rest of Chile	Power Plant Emissions	Chilean Power plant emissions standard (KAS 2009)	PM10, PM2.5, CO, NOX, SOX, VOC, NH3	2009
Rest of Chile	Smelter emissions	Chilean Air Quality Standards Revision (Mena-Carrasco 2010)	PM10, PM2.5, CO, NOX, SOX, VOC, NH3	2010
Rest of Chile	Mobile sources	SECTRA REGIONAL(Corvalan, Osses et al. 2005)	PM10, PM2.5, CO, NOX, VOC	2005
Rest of Domain	Total Anthropogenic excluding power and smelting	EDGAR 3.2 (Olivier, Bouwman et al. 1994)	PM10, PM2.5, CO, NOX, SOX, VOC, NH3	2005
Rest of domain	Total anthropogenic	Bond (Bond, Streets et al. 2004)	Black carbon and organic carbon	2005

1.2.1 Residential emissions

Residential emissions account for 19% of primary PM2.5 emissions according to the official inventory. However, these are annual totals that do not account for seasonality. To distribute seasonal emissions of residential emissions the "heating degree days" concept was used to distribute annual emissions into monthly emissions based on heating demand. Heating degree days are the sum of total daily deviation of mean temperature with respect to a reference temperature. Residential emissions are distributed geographically based on population density(Vijayaraj V. 2007) and percentage of homes using wood burning stoves based on the 2002 census, which are disaggregated to a municipality level. The diurnal profile of emissions is using constant emissions occurring from 6PM to 1AM based on surveys of wood burning use in Chile).

There has been large discussion on how much residential wood burning contributes to bad air quality. Air quality episodes are defined as when one of the 11 monitoring stations present 24h PM10 means above 195ug/m3. Figure 2 shows that most episodes occur between April and August, peaking in May. However, bad air days represent overcoming thresholds of episodic nature, which are only indirectly related to emissions.

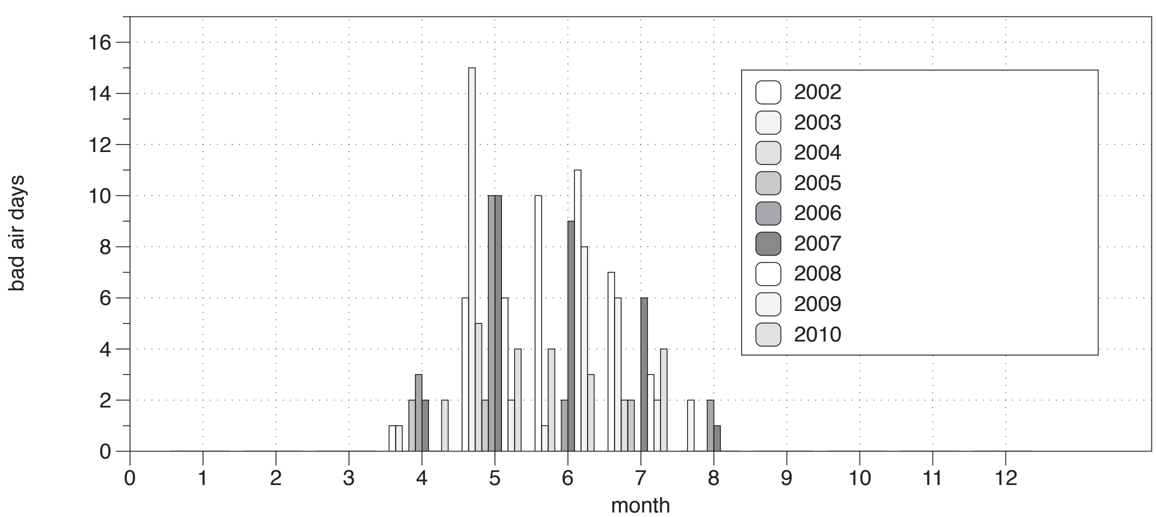


Figure 2 Number of bad air days (PM10 24h means over 195ug/m3) for Santiago during 2002 to 2010 Period

The concept of heating degree days was used was used to quantitatively evaluate if there was a relationship between heating and bad air quality. Heating degree days (HDD) are the difference between daily temperatures is considered confortable (usually 18C) (Jeong, Kim et al. 2011). Monthly HDD were obtained from the Chilean Meteorological Organization from 2002 to 2010 and compared to mean monthly PM2.5 averages for the same period for the MACAM monitoring network for Santiago. It is thought that HDD is a good surrogate for heating requirements for the region, i.e. residential heating emissions. Figure 3 shows HDD vs. monthly PM2.5 means for the period between 2002-2010. As expected, air quality worsens as cold weather sets in.

The linear correlation coefficient, R, between HDD and PM2.5 is 0.73. This value is even higher when days with precipitation are excluded.

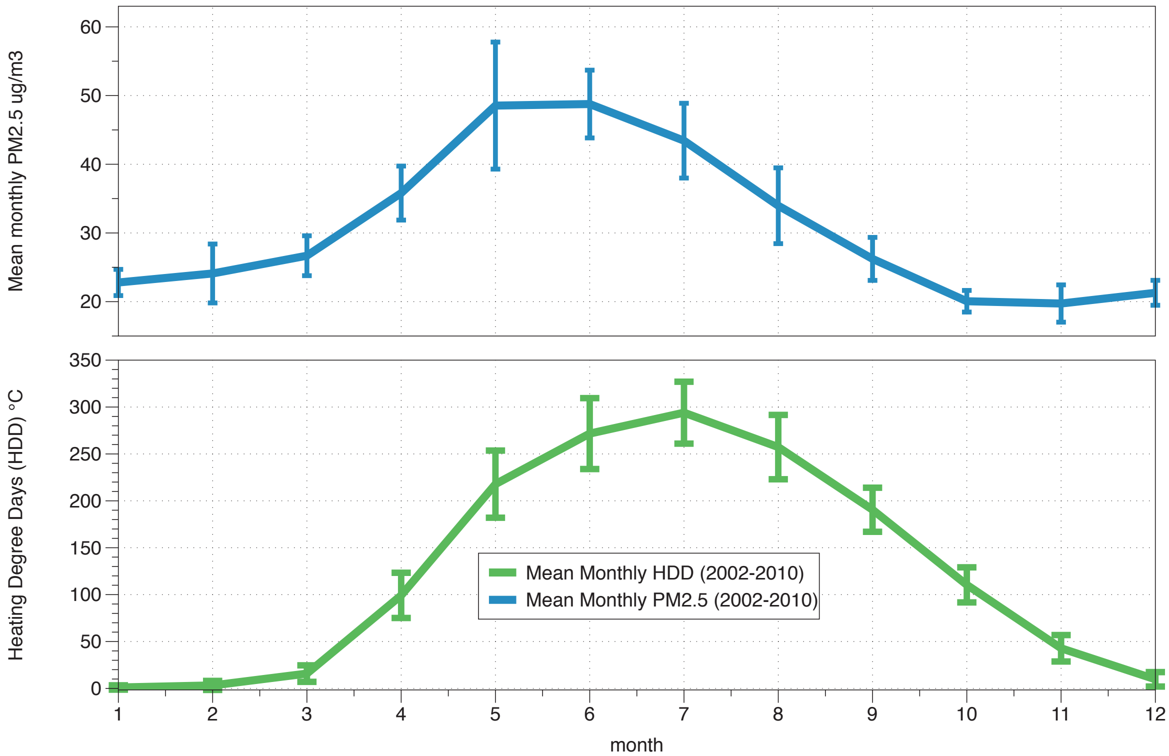


Figure 3 Top: Monthly mean PM2.5 averages for MACAM network (2002-2010), ug/m3. Bottom: Mean monthly heating degree days (2002-2010), base 18C.

Monthly residential wood burning emissions are therefore distributed proportional to monthly heating degree days for Santiago from 2002-2010. Figure 4 that residential wood burning contributes between 40 to 49% of primary PM2.5 emissions during the period.

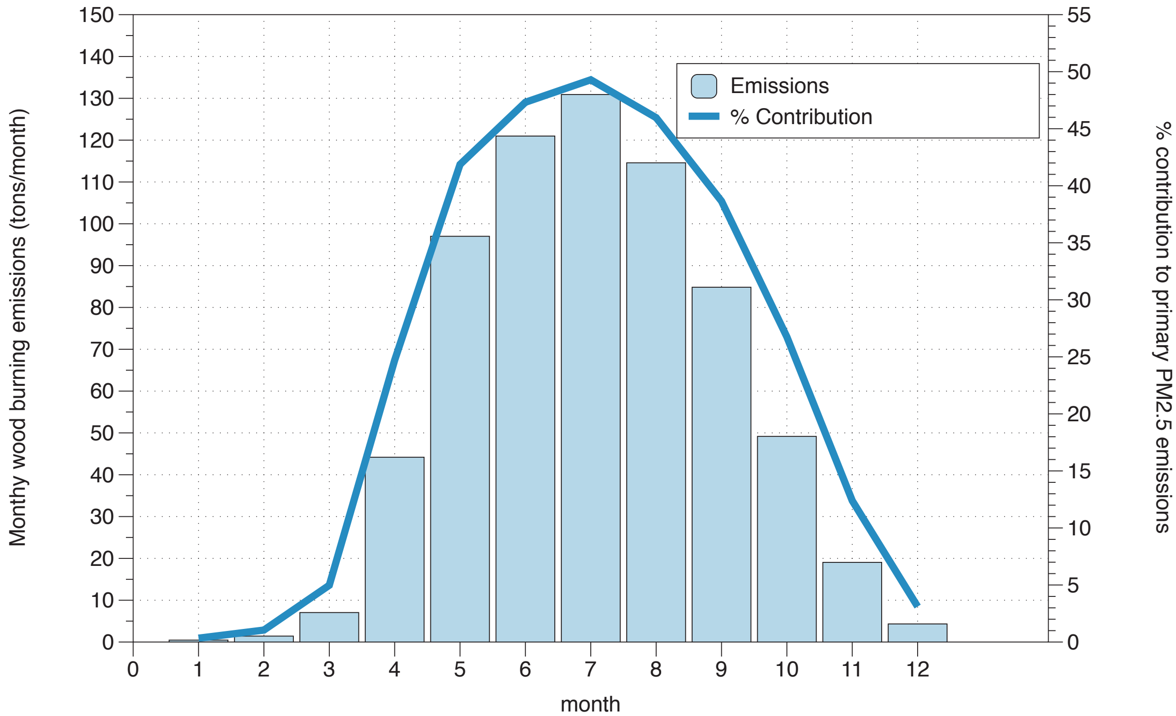


Figure 4 Distribution of wood burning emissions in Santiago based on heating degree days. In bars: monthly primary PM2.5 emissions (tons/month) totaling 674tons/year. Line: Percent contribution of monthly emissions from wood burning to total Santiago primary PM2.5 emissions

1.2.2 Mobile Sources

Mobile sources were updated for 2010 using the SECTRA inventory derived from transit model simulations using the MODEM model (SECTRA 2010). The MODEM model divides Santiago into 9 transit areas, each with a diurnal profile. Emissions are distributed geographically based on LANDSCAN 2008, and temporally based on SECTRA diurnal profiles, which as proven to show similar results than more complex methods (Saide, Zah et al. 2009). Using LANDSCAN data was key in incorporating new highways that were absent in the 2005 official inventory, as urban sprawl and the advent of urban private highways occurred since then. Finally, resuspended dust is also distributed under the same criteria. Total resuspended emissions from car traffic Santiago were estimated in 6000 tons/year for PM10, and 1135tons/year from PM2.5 derived from previous estimations for the area using inverse modeling (Jorquera and Castro 2010), which showed the official values of 19670 and 2766 tons/year of PM10 and PM2.5 were overestimated.

1.2.3 Point sources

Point source emissions for the country collected from emissions inventories that were prepared for pollution prevention plans for areas in non-attainment. For Santiago roughly 1200 point sources are obtained from the official emissions inventories. Outside of Santiago more sources are considered, including power plants emissions obtained from a survey to the electric sector (KAS, 2009). Emissions for the largest sources in Santiago were directly measured, while other smaller sources are estimated from emission factors, mainly the EPA AP-42 database.* A constant emission profile is used for point sources.

1.3 Scenarios

Three scenarios were evaluated for the project, a base scenario, a scenario without residential emissions, and a scenario with natural gas powered public transportation system replacing diesel emissions. These scenarios are intended to evaluate the effect of each sector that is analyzed (heating, public transportation), as this effect will be evaluated as the difference between the base scenario and the controlled scenario.

A scenario was built by estimating reduced emissions from switching the complete bus system, including urban, suburban, and commercial buses (consisting of a small portion of Euro I and a larger proportion of Euro II and Euro III buses) to Euro V compressed natural gas buses with Cummins engines. Reductions were estimated assigning COPERT IV† emissions factors(Ekstrom, Sjodin et al. 2004) to each bus category and compared to compressed natural gas buses with Enhanced Environmentally Friendly Vehicles emissions standard (EEV). In reductions for PM emissions range from 99.4% for conventional diesel technology, to 98-99% for Euro I,II, and III. For this scenario a total reduction of 229 tons/year of PM2.5 was estimated. For NO_x this reduction is estimated at 4763 tons/year, as CNG emissions represent roughly 75% less than Euro I to III. VOC emissions are reduced by 728 tons/year. SO2 emissions are estimated to be reduced by 25tons/year This scenario does not incorporate seasonality.

Another scenario is built by estimating the reduced emissions from replacing wood burning with the current mix of kerosene, natural gas, and propane shown in the official inventory. This scenario incorporates seasonality as is described before. Reductions in PM2.5 are 671tons/year, and VOC's by 7,461 tons/year.
Table 3 summarizes the total primary emissions for Metropolitan Santiago and reductions associated to the scenarios analyzed.

Table 3 Emissions scenarios for compressed natural gas public transportation and cleaner heating (tons/year)

Year	$PM_{2.5}$	CO	NO_X	VOC´s	SO_x
Base Scenario	2,857	547,787	65,049	63.781	5,694

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† http://www.emisia.com/copert/

Reductions					
CNG transportation	229	203	4,763	728	25
Cleaner heating	671	8,223	44	7,461	1

Figure 5 shows the summary of the base emissions scenario for PM2.5 primary anthropogenic emissions, specifically for Winter residential emissions, which includes areas beyond the metropolitan region of Santiago, and regional peaks in Eastern Santiago.

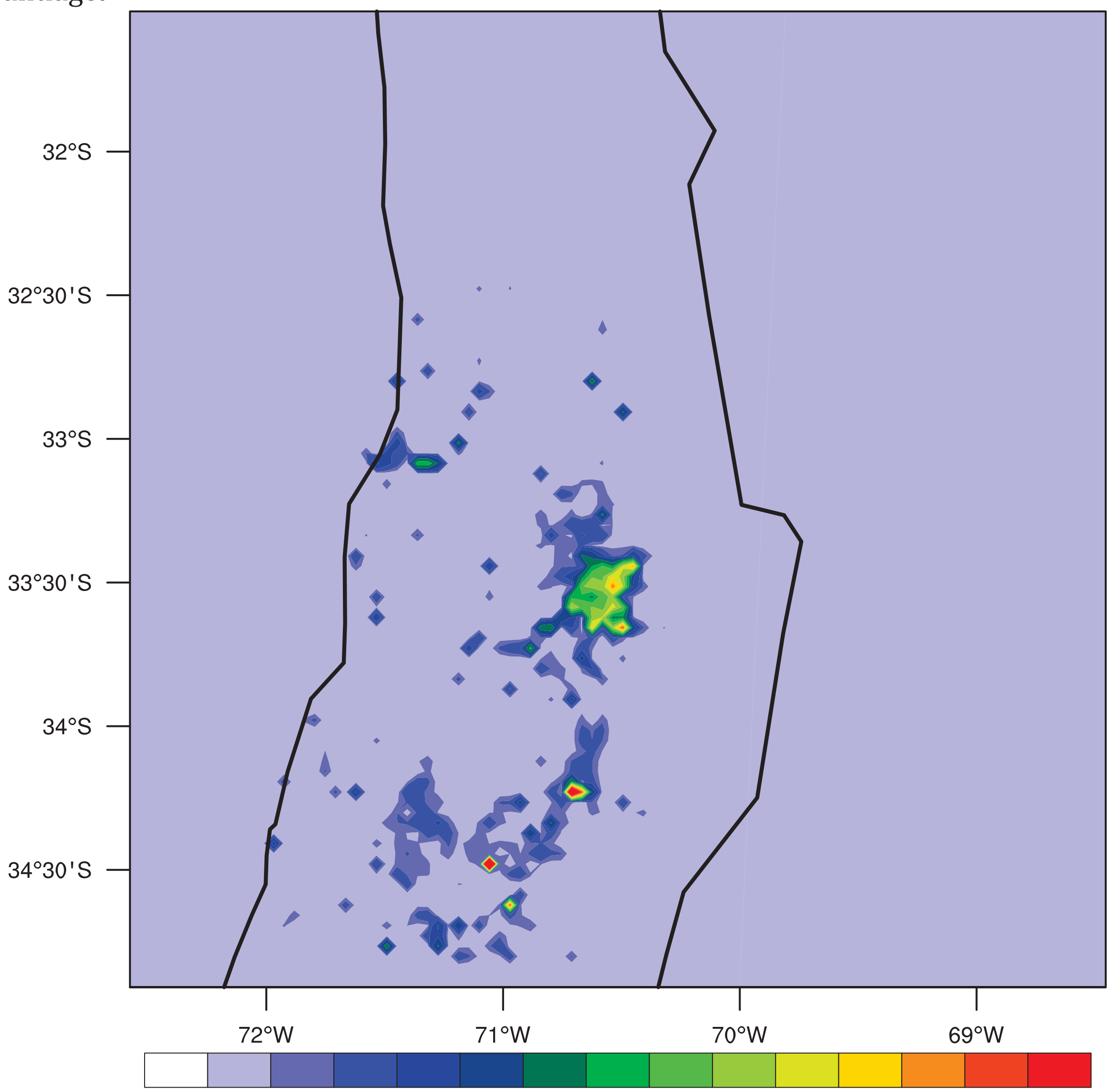

Figure 5 Mean primary anthropogenic PM2.5 emissions for model domain, 4km resolution, in ug/m²/s, using Winter residential heating emissions

Figure 6 shows the scenarios that were considered for the study, including the seasonal distribution of primary PM2.5 emissions for cleaner heating, and for the CNG public transportation scenario. Residential wood burning emissions concentrate in the E/NE portion of the city, and concentrated along residential areas, while the CNG public transportation scenario emissions are much smaller, have no seasonality, and are more evenly distributed.

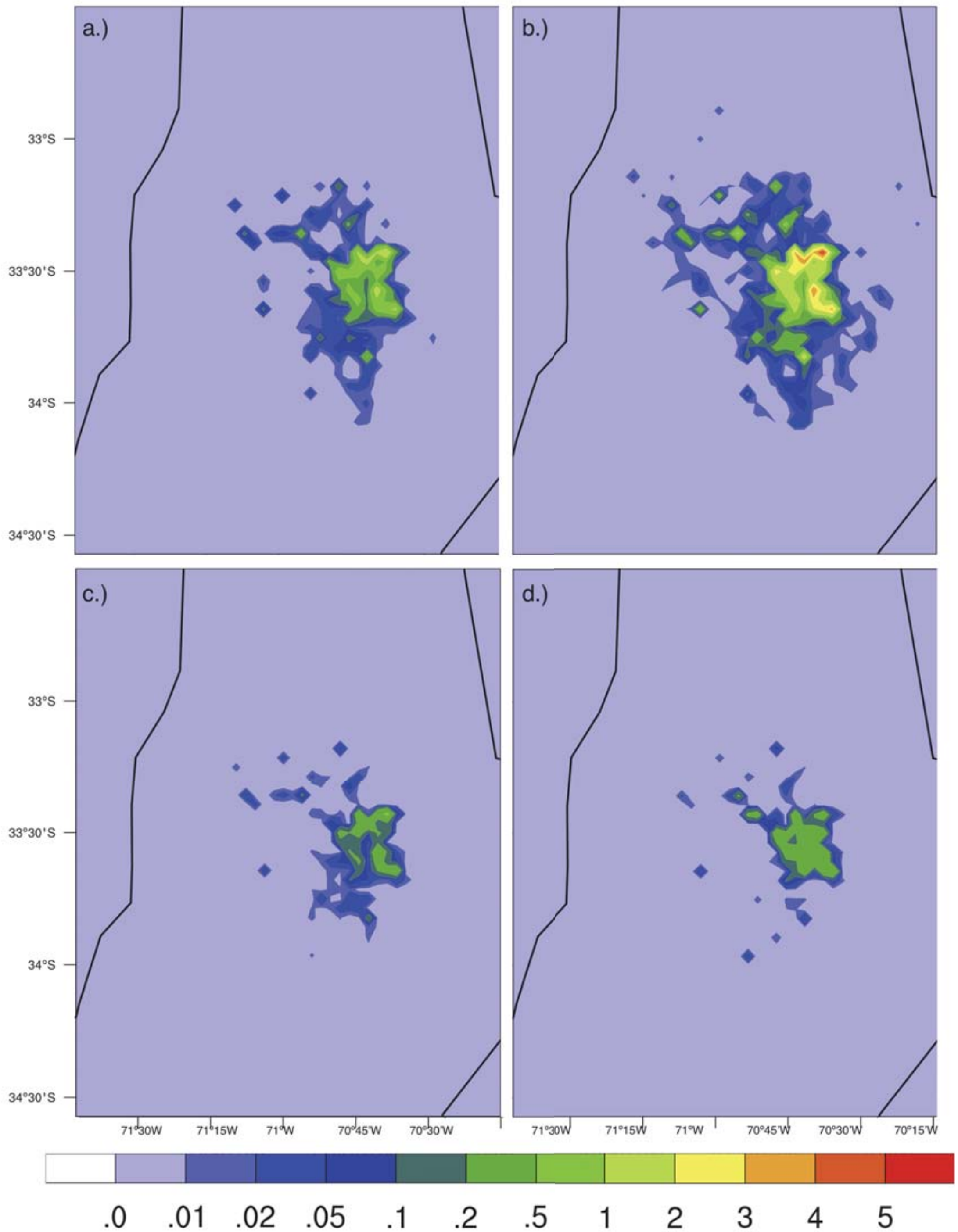

Figure 6 Mean anthropogenic emission reductions (in ug/m2/s). a.) Spring/Fall cleaner heating b) Winter cleaner heating. c.) Summer residential wood burning emissions d) Bus transportation system reductions. (no seasonality).

1.4 Estimation of health benefits.

Health benefits of the emissions reductions described in the scenarios are estimated based on increased health effects

Increased health effects per unit of pollution and population are estimated based on base incidences of health effects and dose response functions. These have been combined for Santiago by Cifuentes et al. (2008) as is shown in Table 4. For this study population distributions are obtained from the LANDSCAN database* for 2008, which a total of 6.396.127 for the metropolitan region of Santiago(vs 6.061.185 from the 2002 census). Population densities are derived from satellite images from 2008 showing "ambient population" based on nighttime lighting. Population densities are regridded from a 0.9km to a 4km resolution through ARCMAP.

Table 4 Health benefits (cases avoided) per million people and ug/m3 of PM2.5, and a 90% confidence interval

Effect	Mean value	90% confidence interval
Premature mortality (acute)	5	3-8
Premature mortality (chronic)	33	21-44
Hospital admissions	22	15-30
Chronic bronchitis	34	19-45
Acute bronchitis	57	0-85
Emergency room visits	133	49-214
Asthma attacks	1.216	462-1.970
Days of work lost	10.225	8.998-11.452
Respiratory symptoms	34.984	29.736-40.232

1.4.1 Economic evaluation of benefits

Individual health benefits are valued based on willingness to pay or cost of illness methods (Cifuentes, 2005). The US EPA has published reference values (EPA, 2009) which can be transferred to other countries through some relationships (Cifuentes, 2005), under the following expression

$$\text{Local value} = \text{USA value} * (\text{Chilean per capita income}/\ \text{US per capita income})^{\text{Elasticity}}$$

Where a value of 1 is used for elasticity(Cifuentes, 2005). Table 5 shows the results for transferring the US reference values to local values for Chile.

* http://www.ornl.gov/sci/landscan/

3. Results

The estimation of benefits is calculated as the difference between the base case and the a model run which includes all emissions minus the emissions that are analyzed. These are done for a total of 1 year, using base year 2008. Mean reductions due to replacing diesel buses with CNG buses are shown in Figure 7 and Figure 8. Maximum reductions in the winter reach 0.8, whereas reductions over 0.2ug/m3 are seen as far as Lampa. During the rest of the year reductions reach a maximum of 0.6ug/m^3, but generally reaching 0.4 ug/m^3. For each grid cell health effects are calculated under the expression

$$Efecto = \sum \Delta C_i * E * P_i$$

Using the method it is estimated that 81 premature mortality cases are prevented under the CNG scenario. A summary of all health benefits is show in Table 6. The economics benefits of the scenario are 200 million dollars per year, but ranging between 126 an 273 million dollars per year (Table 7). These values represent an annual reduction of 0.33ug/m3 for the model domain, with peaks of 0.8ug/m3 reductions in highly populated areas. This result is similar to the health benefits calculated in the 2008 analysis of the Santiago Pollution Prevention Plan (PPDA).

Table 5 Economic valuation of health effects under the Clean Air Act 1990-2010 (Environmental Protection Agency, USA)

Health Effect	Original values 1999(USD)	Inflation adjusted 2008 values (USD)	2008 values for Chile (USD)
Mortality	4.800.000	7.907.078	2.451.194
Hospital admissions for respiratory disease	6.900	11.366,43	3.523,59
Emergency room visits due to asthma attacks	194	319,58	99,07
Astha Attack	32	52,71	16,34
Days of restricted activity	73,72	121,44	36,65

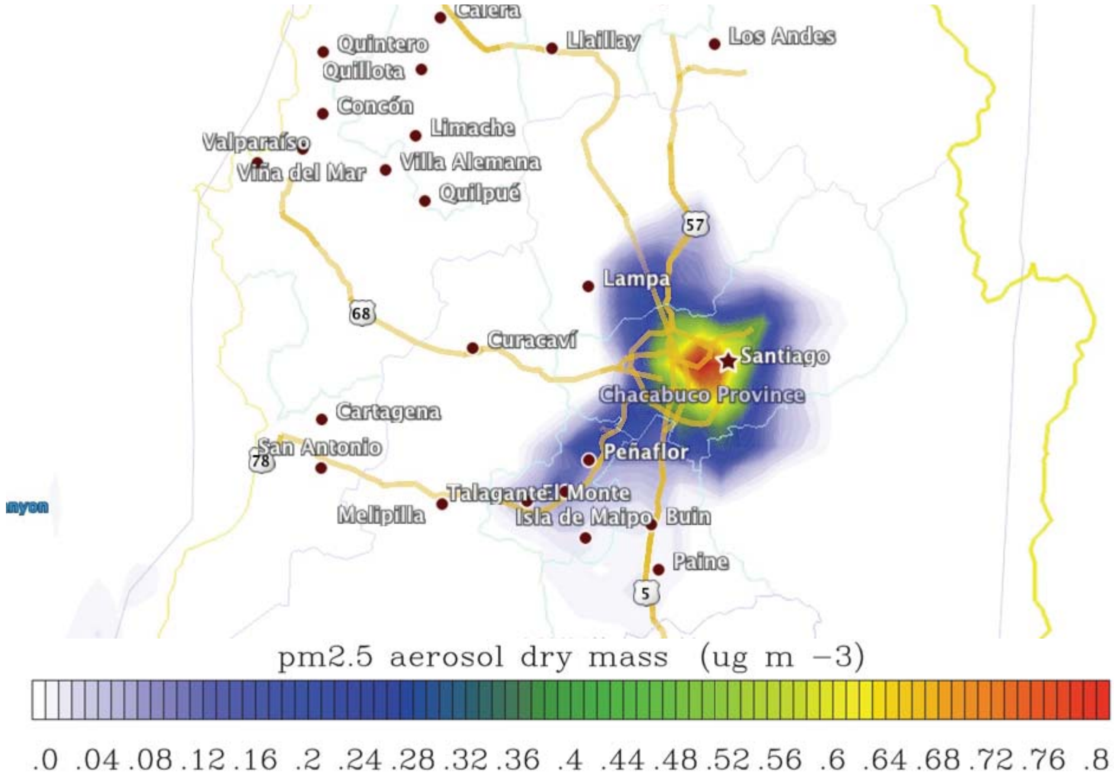

Figure 7 Change in PM2.5 concentrations due to reductions of emissions from CNG scenario for 2008 winter (4km WRF-Chem model, CADM chemistry, and GOCART aerosols scheme)

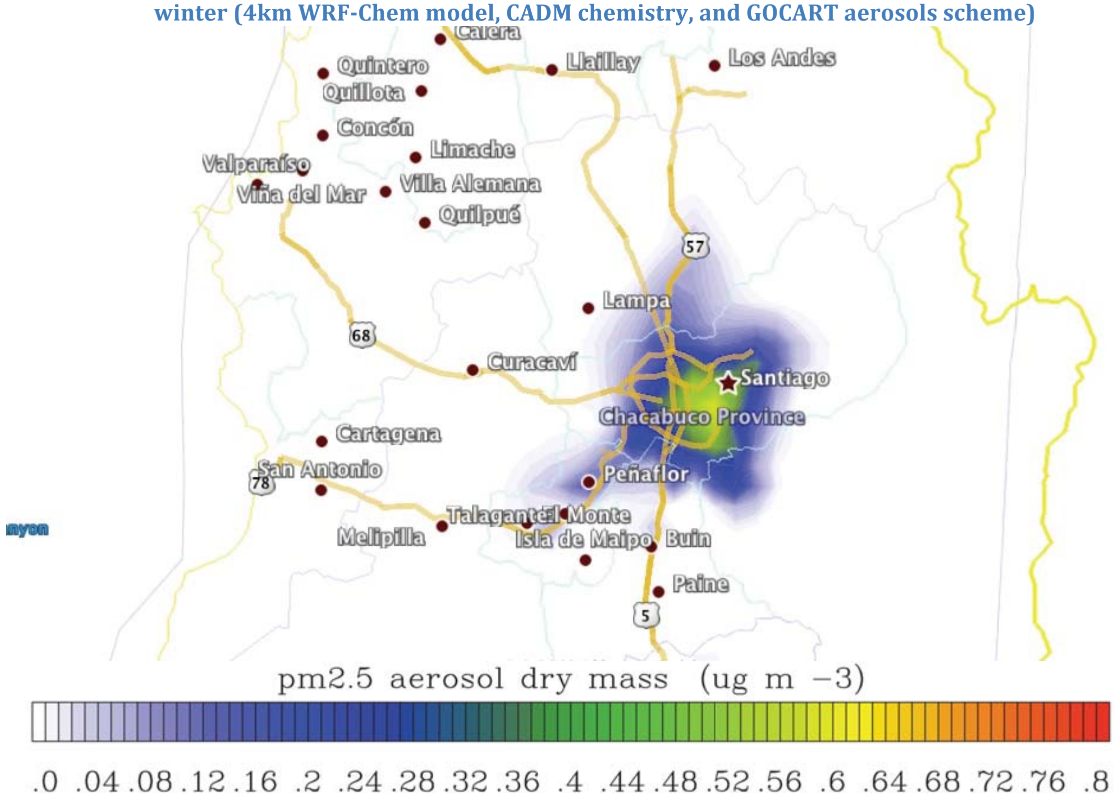

Figure 8 Change in PM2.5 concentrations due to reductions of emissions from CNG scenario for 2008 spring/summer period (4km WRF-Chem model, CADM chemistry, and GOCART aerosols scheme)

Table 6 Summary of health benefits (cases avoided per year) for CNG buses, base don coupling dispersión model (WRF-Chem) and dose response functions

Effect	Medium value	Low range	High range
Premature mortality (acute)	11	6	17
Premature mortality (chronic)	70	45	94
Hospital admissions	47	32	64
Chronic bronchitis	72	40	96
Acute bronchitis	121	0	181
Emergency room visits	283	104	456
Asthma attacks	2.590	984	4.196
Days of work lost	21.779	19.166	24.393
Respiratory symptoms	74.516	63.338	85.694

Table 7 Economic evaluation of health benefits of CNG scenario

Effect	Medium value	Low range	High range
Premature mortality (acute)	26.105.216	15,663,130	41,768,346
Premature mortality (chronic)	172.294.426	109,641,908	229,725,902
Hospital admissions	165,088	112,560	225,120
Chronic bronchitis	42,477	16,139	68,816
Acute bronchitis	798,210	702,424	893,995
Total	**199,405,417**	**126,136,160**	**272,682,178**

Finally the same calculation is performed for residential wood burning. Figure 9 shows that during the winter a maximum of 8ug/m3 are reduced on average (almost 10 times larger than CNG cases). A total of 503 premature mortality cases are prevented under this scenario. Table 8 shows a summary of the total benefits. Total benefits are valued at 1.2 billion dollars per year. Considering that 110,000 wood burning stoves are operating in Santiago, it is estimated that each stove generated healths effects of 11000USD/year.

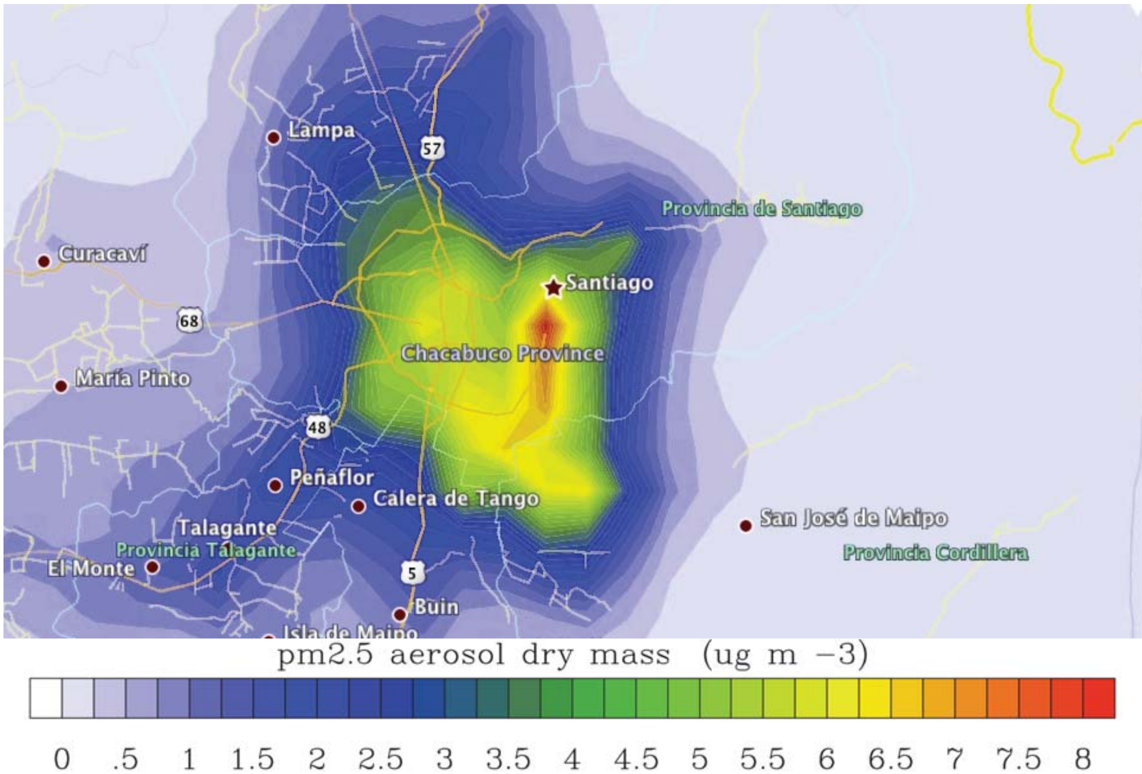

Figure 9 Change in PM2.5 concentrations due to reductions of emissions from clean residential heating scenario for 2008 winter (4km WRF-Chem model, CADM chemistry, and GOCART aerosols scheme)

Table 8 Summary of health benefits (cases avoided per year) for clean residential heating, based on coupling dispersión model (WRF-Chem) and dose response functions

Effect	Medium range	Low range	High range
Premature mortality (acute)	66	40	106
Premature mortality (chronic)	437	278	583
Hospital admissions	291	199	397
Chronic bronchitis	450	252	596
Acute bronchitis	755	0	1,125
Emergency room visits	1,761	649	2,833
Asthma attacks	16,100	6,117	26,083
Days of work lost	135,379	119,134	151,624
Respiratory symptoms	463,188	393,705	532,672

Table 9 Economic evaluation of health benefits of residential heating scenario

Effect	Medium value	Low range	High range
Premature mortality (acute)	162,269,043	97,361,426	259,630,468
Premature mortality (chronic)	1,070,975,682	681,529,980	1,427,967,577
Hospital admissions	1,026,179	699,668	1,399,336

Chronic bronchitis	264,037	100,317	427,758
Acute bronchitis	4,961,640	4,366,244	5,557,037
Total	1,239,496,582	784,057,634	1,694,982,176

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