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Compilation of a GIS based high spatially and temporally resolved emission inventory for the greater Istanbul area

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ABSTRACT

Emission inventories are a fundamental input to atmospheric chemical transport models (CTMs). As the latter become increasingly demanding, modern inventories began to provide much more information (high spatial and temporal disaggregation, more chemical compounds etc). In this study we present a computational approach, an emission processing kernel that is used to compile a high spatially and temporally resolved emission inventory for the anthropogenic sources covering the Greater Istanbul Area (GIA) for the reference year 2007. The emission processor is used to produce emissions for a 92 x 57 km area covering the GIA with 2 km grid resolution. The emission inventory has high temporal resolution, covering monthly, weekly and diurnal processing and includes CO, NO_x, SO_x, NH_3, and chemically speciated PM_{10}, $PM_{2.5}$ and NMVOCs emissions. PM_{10} and $PM_{2.5}$ are chemically split into organic carbon, elemental carbon, sulfates, nitrates, ammonium and other particles while NMVOCs are chemically speciated into 23 chemical compounds. The compilation process includes the use of various activity information and statistical data that were gathered from local official authorities and experts, measurements, published studies for the region or extracted from pre–existing databases. The results indicate that the road transport sector is the main contributor to the emissions in the area, whereas residential combustion (for SO_x) and solvent use (for NMVOCs) are also important source categories. Industrial combustion is found out to be the main SO_x emitter. The temporal calculations show that monthly distributions follow the seasonal variation for most of the pollutants with higher emissions in winter time. Diurnal calculations show that the profile fits with the rush hours due to the highest contribution of traffic emissions.

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1. Introduction

Emission inventories provide critical information for decision–makers through the use of air quality modeling by quantifying the impact of different sources. Their importance in air quality modeling has been pointed out by many authors (Russell and Dennis, 2000; Hanna et al., 2001; Poupkou et al., 2008). Emission inventories represent the amount of pollutants emitted to the atmosphere from a specific area (i.e. local to global) during a specific time period (i.e., past to future), originated from anthro–pogenic or natural activities (Sofiev et al., 2006; Sofiev et al., 2008). Emission sources are broadly classified to point, area and mobile sources. For air quality modeling purposes, emissions should be spatially distributed over a domain, temporally resolved, and finally, chemically speciated into individual species or groups of species (Zanis et al., 2007; Borge et al., 2008; Ganev et al., 2008).

In order to achieve these requirements, modern tools such as Geographical Information System (GIS) software and GIS techniques can be implemented (Markakis et al., 2010b). GIS environment can be the basis for the compilation of spatially and temporally resolved emission inventories which are easily updated and can efficiently derive the demanding input fields of air quality models. Hence, these tools are increasingly being used for environmental modeling studies and air pollution analysis as they provide an integrated framework for the quantification of emissions and/or spatial data analysis (Poupkou et al., 2007; Symeonidis et al., 2007; Markakis et al., 2010a).

The city of Istanbul is one of the megacities of the world with more than 12 million inhabitants (TUIK, 2007). Air pollution is a major concern for the citizens of Istanbul. Within the last 40 years, the city has experienced a rapid growth in urbanization and industrialization (Governorship of Istanbul, 2005). The region experiences very dense industrial activities, almost the highest in the country (The Union of Chambers and Commodity Exchanges of Turkey, 2009). Approximately 37% of the industrial activities in Istanbul originate from the textile industry, 30% from the metal industry, 21% from the chemical industry, 5% from the food industry and 7% from other industries (Governorship of Istanbul, 2005). The city is divided into the European and the Asian sides by the Bosporus, a seawater strait extending from the Black Sea in the north and the interior Marmara Sea in the south. Local ferries play an important role in the transportation within the city. The Bosporus strait serves as a passage linking Black Sea to Aegean and thus the Mediterranean Sea leading to intense international shipping activity through the city. Under these dense and variety of industrial activities, the region is exposed to high pollutant concentrations considering secondary pollutants like ozone, for which the levels have exceed 73 ppb and reach up to 150 ppb (Im et al., 2006; Im et al., 2008) and particulate matter, where the annual mean values were higher than the European Union annual PM_{10} standard of 40 μg m^{-3} (Tayanc, 2000; Karaca et al., 2005).

According to the air quality network of the Ministry of Environ–ment and Forestry, the annual mean value of PM_{10} concentrations exceed the limit of 40 μg m^{-3} at all 10 municipality stations with an overall average of 58.7 μg m^{-3}. The number of days exceeding the 24–hour limit value of 50 μg m^{-3} was 157 days (on average from all stations) whereas the limit is 35 days.

Several studies were conducted that focused on compiling emission inventories for Turkey (Ekinci et al., 1998; Muezzinoglu et al., 1998; Elbir et al., 2000; Goncaloglu, 2001; Soylu, 2007; Kesgin and Vardar, 2001; Canpolat et al., 2002; Dincer et al., 2003; Muezzinoglu et al., 2003; Elbir, 2004; Elbir and Muezzinoglu, 2004; Skouloudis, 2005; Kesgin, 2006; Say, 2006; Yay et al., 2006; Cetin et al., 2007; Dincer and Elbir, 2007; Elbir, 2008; Deniz and Durmusoglu, 2008, Elbir et al., 2010). However, none of these studies provides comprehensive information on Istanbul's emissions. The majority of the above mentioned studies present one or more of the following limitations: they are compiled for one specific source sector or pollutant, they present emissions on national level, they are not gridded or temporally varied or they present old and outdated data. The motivation of this work is to provide an insight regarding the potentials for the major gaseous and particulate matter emissions from all anthropogenic sources in the city of Istanbul. Additionally, in order to support ongoing air quality modeling applications, in the area, which are supported by a number of funds from COST 728 Action and the Scientific and Technological Research Council of Turkey (TUBITAK), a chemically speciated and model–ready inventory has been compiled. The inventory covers the Greater Istanbul Area (GIA) with 2 km spatial and hourly temporal resolution for the reference year 2007. The best available activity and statistical data have been combined with geographical information and scripted into GIS software to produce hourly gridded emission fields for 16 gaseous/PM compounds and 23 non– methane volatile organic compounds (NMVOC) species or groups of species.

2. Materials and Methods

2.1. General description of the inventory

This work aims to quantify the emissions for the GIA, and in addition to act as a base for ongoing air quality modeling studies for the city of Istanbul. This ongoing research covers high reso–lution simulations of high ozone and aerosol levels in Istanbul within the framework of the COST 728 Action project and the National Geodesy and Geophysics Union of Turkey (TUJJB) project. For this reason emissions are spatially allocated on a 92 × 57 cells grid using a grid spacing of 2 km over the GIA (Figure 1). The emissions are projected in Lambert Conformal Conic (LCC) covering an area of 20 976 km^2. The pollutants considered are nitrogen oxides ($NO_x = NO + NO_2$), carbon monoxide (CO), sulfur oxides (SO_x), ammonia (NH_3), non–methane volatile organic compounds (NMVOCs), PM_{10} (particulate matter of less than 10 μm in diameter) and $PM_{2.5}$ (particulate matter of less than 2.5 μm in diameter).

The emission inventory includes all anthropogenic emission sources (the Selected Nomenclature for sources of Air Pollution, namely the SNAP macrosector in which each emissions activity belongs is included in brackets): energy production (SNAP1), residential central heating (SNAP2), industrial combustion (SNAP3), industrial processes (SNAP4), coal extraction (SNAP5), distribution of fuels (SNAP5), solvents use (SNAP6), road transport (SNAP7), off–road vehicles and machinery (consisting of construction and other industrial vehicles/machinery, agriculture, forestry, house–hold and gardening vehicles/machinery and railway transport) (SNAP8), aviation (SNAP8), cargo shipping (SNAP8), local ferries (SNAP8), waste treatment and disposal (SNAP9) and agriculture (SNAP10). The compilation process includes the use of:

(a) Activity information and statistical data that were gathered from local official authorities and experts are used for the quantification of emissions for the energy sector (Ambarli power plant), residential and industrial combustion sectors, solvents use, coal extraction, local ferries and cargo shipping.

(b) Measurements of emission fluxes (Energy sector – Esenyurt power plant).

(c) Emissions derived from studies conducted in the region by other researchers (road transport and aviation sectors).

(d) Emissions extracted from pre–existing gridded invent–tories (industrial processes, distribution of fuels, off–road vehicles and machinery, waste treatment and disposal and agriculture). For this task the high resolution emission inventory of Visschedijk and Denier van der Gon (2005); Visschedijk et al. (2007) (hereafter referred as TNO) was used detailed information of which can be found in Section 2.4.

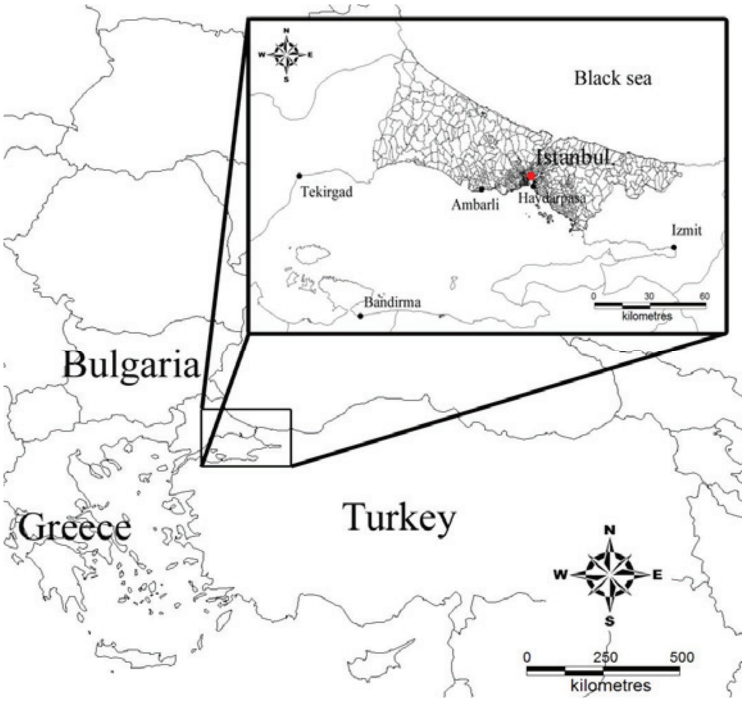

Figure 1. *Overview of the study area. The municipalities of Istanbul are shown in the figure.*

Table 1 summarizes all the input activity data used in this work. The emissions of Biogenic VOCs (BVOCs) are not taken into account since this work principally focuses on anthropogenic emissions.

Finally the emissions of this inventory are considered representative for 2007 and adjustment years. It must be noted though that not all the information used in the present study correspond to the same year. The information used though for the compilation of emissions for the most important and contributing sources are relevant for 2007 (residential and industrial combustion, cargo shipping) and 2008 (road transport). Note also that in the current work no effort has been undertaken in order to bring up to date the emission data representative for past years.

2.2. Description of the emission processor

To provide easy updatability, the inventory was compiled by each source sector or subsector using an emission processing kernel developed for this purpose. The emission processor is coded in Mapbasic 9.0 programming language and it uses the Mapinfo 9.0 GIS software as the computing platform. The processor is structured to yield spatially and temporally disaggregated emissions for 39 chemical species/groups of species starting from input activity data or the pre–existing emission totals. Figure 2 presents a schematic description of the emission processor.

Table 1. *Major characteristics of the emission sources of the GIA emission inventory. Bold letters in the source category column signify the sources for which emissions were quantified whereas in italics sources for which emissions were taken from pre–compiled databases*

Source category	Type of input data	Source of input data[a]/ emission factors	PM chemical profile[b]	Spatial allocation method
Energy[c]	Esenyurt Unit–stack measurements Ambarli Unit–consumption of fuels	IMM, EGC/USEPA (1995)	**NG:** GMC, **Oil:** FCR	Geographical coordinates
Residential combustion	Consumption of NG, oil, coal	IGDC, IMM/USEPA (1995)	**NG:** RNG, **Oil:** LMC, **Coal:** CCC	Population density
Industrial combustion	Consumption of NG, oil, coal, LPG	IBB/USEPA (1995)	**NG/LPG:** ICEG, **Oil:** FCR, **Coal:** ICES	Organized Industrial Areas (OIA)
Coal extraction	Extracted quantities of coal	Mining companies/CEPMEIP	All particles as "OTHER"	Coal extraction areas
Solvents use	Population in the neighborhoods	IBB/USEPA (1995)	No PM emissions	Population density
Road transport	EMBARQ (2007)	EMBARQ (2007)	Diesel Vehicle Exhaust	Road length
Local ferries	Fuel consumption	IFF/CORINAIR	FCD	Operating lines
Cargo shipping	Vessel traffic in the Bosporus straight and the Ambarli port	UMA (2007), Kılıc (2006)/ CORINAIR, Cooper and Gustafsson (2004)	FCR	Cruising lines
Aviation	Kesgin (2006)	Kesgin (2006)	Aircraft – Jet Fuel	Geographical coordinates[d]
• *Industrial processes* • *Distribution of fuels* • *Off–road vehicles* [f] • *Waste treatment* • *Agriculture*	(Visschedijk and Denier van der Gon , 2005; Visschedijk et al., 2007)	TNO gridded emission database (Visschedijk and Denier van der Gon , 2005; Visschedijk et al., 2007)	EPA AVG: Industrial Manufac. – Diesel Vehicle Exhaust Waste Burning Livestock Operations Dust	OIA (Fuel consumed)[e] Population density Population density Population density USGS landcover[g]

[a] *Abbreviations are:* ***IMM:*** *Istanbul Metropolitan Municipality,* ***EGC:*** *Electrical Generation Co.,* ***IGDC:*** *Istanbul Gas Distribution Corporation,* ***IFF:*** *Istanbul Fast Ferries Co.,* ***IBB:*** *Bogazici University (2007).*

[b] *Profile naming corresponds to that found inside the chemical profiles database file of CARB (2007). Abbreviations are:* ***GMC:*** *Gaseous Material Combustion,* ***FCR:*** *Fuel Combustion – Residual,* ***FCD:*** *Fuel Combustion – Distillate,* ***RNG:*** *Residential – Natural Gas,* ***LMC:*** *Liquid Material Combustion,* ***CCC:*** *Coal/Coke Combustion,* ***ICEG:*** *Stat. I.C. Engine – Gas,* ***ICES:*** *Stat. I.C. Engine – Solid Fuel.*

[c] *The energy sector is partly compiled based on activity data (Ambarli unit) and partly based on pre–compiled emission data (Esenyurt unit).*

[d] *Airports with more than 100 000 annual LTOs (Land/Take off Operations) should be treated as point sources (EMEP/CORINAIR 2001).*

[e] *The emission totals which derive from all the TNO cells in the GIA were reallocated in the 32 OIA based on the consumption of fuels in each OIA.*

[f] *Includes agriculture, construction and other industrial, forestry, household/gardening vehicles and machinery and railway transport.*

[g] *The source of the land use information was the Global Land Cover Characteristics database (GLCC version 2) distributed by US Geological Survey (Loveland et al., 2000). The database elements characterized as crops or mixed (crops/forest) were used as relevant for this source.*

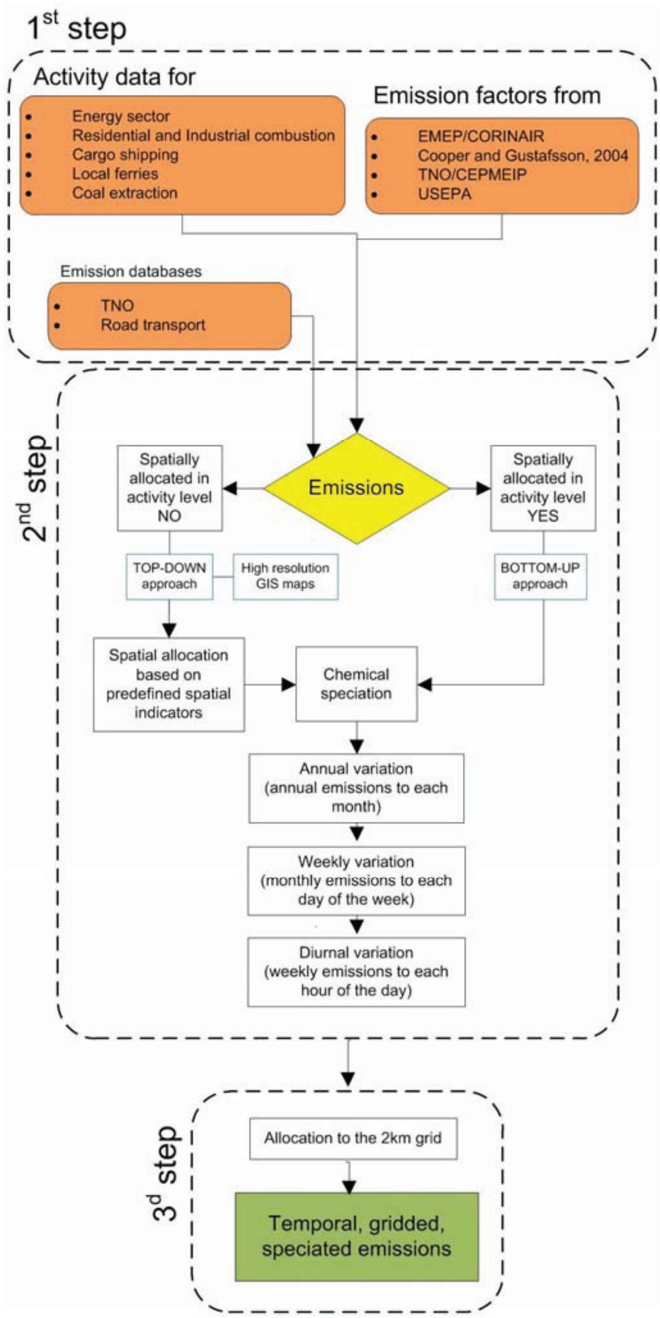

Figure 2. *Schematic diagram of the emission processor.*

The processing is done by source sector and it is summarized in the following procedures:

- Derivation of annual emissions rates (1st step in Figure 2) is completed either by quantifying the emissions using the available activity data or derived from the pre–existing databases e.g. from the gridded emissions of TNO. The processor handles pre–compiled GIS database tables which include all the activity/ statistical information necessary for the calculations as well as the pre–existing emissions data to be processed in the following step.
- Subsequently, the spatial disaggregation of area source emissions is introduced (first part of the 2nd step in Figure 2). Both bottom–up and top–down methodologies were used to downscale the emissions. The terms bottom–up and top–down can be used to define the spatial allocation methodology e.g. a top–down approach suggests the downscaling of emissions utilizing appro–priate spatial proxies whereas a bottom–up approach directly allocates the emissions on their actual activity level. In that context the emissions of the TNO database and the emissions of the road transport sector were scaled down to the 2 km grid employing a top–down approach by utilizing a number of high resolution digital maps such as the road network, population and land uses. More specifically in order to provide spatially resolved emissions, the processor handles geographical maps which are combined with source specific spatial indicator maps. A spatial indicator correlates an emission source with its activity in geographical terms. The spatial indicators are defined based either on geographically resolved official statistics (e.g. population density), data derived from GIS maps (e.g. road network) or on land use data (Loveland et al., 2000). Table 1 summarizes the spatial indicators chosen for use in this work. More detailed, spatial operations are performed with the aim to reallocate the emissions derived from the pre–existing databases to the highest possible spatial level, which represents closest the actual activity of a given sector/subsector. For example to reallocate the gridded emissions of the distribution of fuels sector derived from TNO to the neighborhoods of Istanbul, the population density of each neighborhood within each TNO grid cell was used as the appropriate spatial indicator. These emissions (e.g. the emissions allocated in the neighborhoods) are finally reallocated to the final inventory grid in step 3 (Figure 2). In contrast the bottom–up methodology was used for the emissions of the residential and the industrial combustion, coal extraction, solvent use and the maritime sectors (Table 1). The emissions of the energy and the aviation sector (Ataturk international airport) are allocated in their actual positions and treated as point sources.
- Particulate matter and NMVOCs emissions are chemically speciated (second part of the 2nd step in Figure 2) using the source sectoral profiles of Olivier et al. (2001) and Visschedijk et al. (2007) regarding the NMVOCs and CARB (2007) regarding the PM. The PM chemical profiles chosen for use in this work are tabulated in Table 1. To provide chemically resolved emissions, profile tables are used. The tables contain the chemical profiles which are linked to the emission tables based on source relevant chemical indicators e.g. the type of fuel burned (for residential/industrial combustion). The NMVOCs emissions are chemically speciated in 23 species/groups of species and they are provided per SNAP macrosector e.g. all emission activities within the same SNAP macrosector use the same profile (the profiles are given in the Supplementary Material, SM). The NMVOCs profiles adopted in this study were compiled specifically for Turkey. Furthermore splitting of PM emissions is needed for the characterization of their chemical composition. PM_{10} emissions were chemically speciated into organic and elemental carbon, nitrates, sulfates, ammonium and other particles. A constant value of 0.9 was used for the NO/NO_x fraction for all NO_x emission sectors following USEPA defaults (USEPA, 2006; Borge et al., 2008). Finally it has to be stated that the provided emissions for the 23 NMVOCs species/groups of species are not related to any of the known chemical mechanisms like CB–IV, CB–V, SARPC and others. This provides to the emission inventory user the highest possible information in order to lump the provided NMVOCs species in the speciation of the preferred mechanism.
- Finally the temporal variation of emissions (final part of the 2nd step in Figure 2) is introduced by source sector. Similar to the previous step profile tables are being used which include all the factors to increase the temporal resolution (e.g. to scale the monthly emissions down to weekly emissions, the processor uses 7 factors one for each day of the week). The emissions are temporally resolved using monthly, weekly and diurnal profiles. All temporal variation profiles used in the present paper originate from GENEMIS (1997) and were compiled within the scope of the EUROTRAC/GENEMIS project. The profiles are country specific per SNAP macrosector. The only exception are the diurnal variation for the road transport emissions which were provided by the EMBARQ study (EMBARQ, 2007) and based on camera recordings in 18 sites in the city as well as the monthly variation of international cargo shipping emissions provided by the UMA (2007), as monthly vessel traffic.

The emissions of each source sector are aggregated to produce surrogate files for each of the species considered. It should be stated that the developed emission processor reflects the assembled dataset which subsequently defines the followed methodology (including the quantification processes, the spatial disaggregation method etc.). This limits the ability to use the processor with a more detailed dataset.

2.3. Quantification methodology

For the quantification of emission sources a bottom–up approach was adopted. The term bottom–up defines a metho–dology that implements activity information along with the appropriate emission factors in order to derive the emission totals for a specific source. The quantification of emissions follows the general equation:

$$E_{ij} = e_{ij}A_j \qquad (1)$$

where $E_{i,j}$ is the emission of pollutant *i* released from the activity/process type *j*, $e_{i,j}$ is the emission factor which defines the mass of pollutant *i* being released per unit of activity/process *j* and A_i corresponds to the total activity of the process *j*.

For the quantification of the residential/industrial combustion sectors as well as the energy and the coal extraction sectors the emission factors of USEPA (1995) were used because they are considered more appropriate for the area in comparison to the respective emission factors of the European sources (EMEP/CORINAIR, 2001). USEPA (1995) emission factors represent better the local conditions for example the high–ash, high sulfur content of the fuels used in Turkey as well as the different particulate matter abatement technologies (Muezzinoglu et al., 1998; Elbir et al., 2000; Elbir, 2004; Elbir and Muezzinoglu, 2004). The emission factors for the road transport sector are compiled by EMBARQ (2007) specifically for the city of Istanbul. Detailed description is found in the sub-Section below (Road Transport). As regards the maritime sector the methodology (including the emission factors) of Trozzi and Vaccaro (1998) (which is also adopted by CORINAIR) and Cooper and Gustafsson (2004) were used. These metho-dologies incorporate certain vessel characteristics, they have application on global scale and they are not restricted in local conditions. This approach has been used by other researchers to compile maritime emissions in the area (Kesgin and Vardar, 2001; Deniz and Durmusoglu, 2008).

Residential and industrial combustion. The calculation of the emission rates derived from the residential heating (cooking activities are not included) was based on the annual consumption of natural gas (NG), light fuel oil, coal, liquefied petroleum gas (LPG) and the emissions factors derived from USEPA (1995). The consumption of residential natural gas was provided in a spatial level representing the neighborhoods of the GIA from the Istanbul Gas Distribution Corporation (IGDAS). In this study the boundaries of 640 administrative units representing the neighborhoods of the city are provided in a high resolution digital database. The total amount of coal used in the city for residential heating was provided from the Istanbul Metropolitan Municipality. To distribute that amount to each municipality a relationship which takes into account the penetration of NG as well as the population density in each neighborhood was used. An equal contribution of the two factors to the final relationship was assumed. Consequently:

$$FC_{coal,i} = 0.5\, F_{coal,tot}\left[\left(\frac{PD_i}{PD_{tot}}\right) + \left(\frac{NG_i}{NG_{tot}}\right)\right] \qquad (2)$$

where FC_{coal} is the consumption of coal in the municipality *i*, $F_{coal,tot}$ is the total amount of coal consumed in the city (1 million tons), PD_i is the population density in the municipality *i*, PD_{tot} is the total population density of all the municipalities of the city, NG_i is the annual consumption of natural gas in the municipality i and NG_{tot} is the total annual consumption of natural gas in the city. The average per capita consumption of coal in Istanbul is estimated in 0.1 t and 386 m^3 for natural gas.

The annual consumption of coal, natural gas, LPG and fuel oil, used in the Organized Industrial Areas (OIA) (33 in total) were provided by IBB (Bogazici University, 2007). Table S1 (see the SM) summarizes the amount of fuels used for the quantification of residential and industrial emissions and Table S2 (see the SM) tabulates the emission factors chosen for use in this work.

For the calculation of SO_x emissions it was necessary to determine the sulfur content of the fuels. For NG and LPG, a value of 0.1% wt was used and for residential/industrial fuel oil, it was taken equal to 1.5% wt (Cetin et al., 2007). For the industrial and residential coal, a value of 1.0% wt was used. This is based on the weighted average of the maximum allowed sulfur content in the city which is 0.9% for local reserves and 1.6% for imported coal. More than 80% of the coal used in the city comes from local reserves.

Public power generation plants. Two power generation plants were included in the emission inventory. For the natural gas power unit of Esenyurt (390 MW), the hourly emissions rates of CO, NO_x, SO_2 (used as SO_x) and TSP (total suspended particulates) were obtained from the emission reports provided to IBB and are based on stack–gas measurements conducted in August, 2003. In order to derive annual emissions from the hourly measured rates, 7 000 hours of annual operation was used (EMEP/CORINAIR, 2001) based on the assumption that the power plant of Esenyurt is a base load unit, which is under constant load except from the days in maintenance and reduced operating load in certain periods.

In order to estimate the emissions of the Ambarli power plant, which operates one 1 350 MW unit burning natural gas and one 1 205 MW unit burning oil, the annual consumption of natural gas (see the SM, Table S1) and heavy fuel oil, provided by the Electric Generation Co. Inc. (EUAS), was multiplied with emission factors taken from EPA (see the SM, Table S2).

Road transport. Emissions from the road transport are obtained from a study conducted by EMBARQ (World Resources Institute Center for Sustainable Transport) and the Istanbul Metropolitan Municipality's Environmental Protection Division in 2006. The main objectives of the project were to set up an emission factor data–base for diesel and gasoline vehicles in Istanbul (based on on–road testing), collect comprehensive data on vehicle activity and fleet composition and finally to estimate annual on–road vehicle emissions in Istanbul. Details of this study can be found in EMBARQ (2007).

Vehicle activity portion of the emissions inventory project was designed specifically to: (i) define the on–road fleet composition by vehicle class, engine size, emissions technology, fuel type, vehicle age, etc., (ii) understand the traffic flow using GPS data (accele–rations, etc), (iii) understand vehicle use and (iv) to observe driving behavior. Consequently, measurements of the vehicle driving pattern, the video surveys and parking lot surveys were conducted by three teams (assigned to the same neighborhood), on five representative sections of the city (European side, lower and higher income, Asian side, lower and higher income and European commercial). The areas selected were chosen so that they would represent the overall fleet makeup and general driving taking place in the city.

On–road driving varies by time of day, by day of the week, and by location in an urban area. In order to account for this, activity data were collected at different times of the day and in different locations. The technology distribution of vehicles was developed using an approach based on vehicle video survey (more than 13 hours of recorded digital video were inspected) on a variety of roadways and were reviewed by the expert personnel of the

Istanbul Metropolitan Municipality (IMM) who counted the numbers of the various types of vehicles driving on Istanbul's roads. Surveys of parked vehicles (a total number of 2 204 vehicles were inspected) allowed for the careful inspection of vehicles and information regarding data pertaining to the vehicle manufacturer, model, fuel type, model year, license plate number, engine size and technology, add–on control technology, transmission type, and air conditioning equipment were collected.

Vehicle driving patterns were measured using GPS technology, which enables the measurement of vehicle location and speed. For passenger cars, three vehicles were outfitted with GPS and driven on selected city's roadways such as highways, arterials and 9 neighborhood streets (a total of 11 days' data were recorded during the campaign). In addition, GPS devices were also installed on busses, trucks and taxis and a total of 1 008 900 data points were collected for these vehicles. Overall, an average speed of 40 km h^{-1} was observed over highways, 23 km h^{-1} for arterial and 20 km h^{-1} for residential streets.

Second–by–second emissions of CO, NO_x and total hydrocarbons (THC) were measured for 104 gasoline–fueled and 42 diesel–powered vehicles (Including passenger, light and heavy trucks as well as busses) over a three week period using a SEMTECH–G portable emissions monitor with GPS and exhaust flow measurement system (for gasoline vehicles) and a Sensor D testing unit (for diesel vehicles) providing in–use emissions information for vehicles operating in the study area. A Dekati DMM testing unit was used for measuring PM emissions of diesel vehicles. A circular driving route was selected (each route was completed within 35 to 50 minutes) with a variety of driving situ–ations including low speeds on congested arterials and residential streets, as well as higher speeds and accelerations on highways. In order to simulate passenger weight, sandbags were placed on the busses. Subsequent analysis of the data, using the IVEM metho–dology (Davis et al., 2005), provided second by second vehicle power demand (i.e., power required by the vehicle to maintain the required speed and acceleration) in association with the measured emissions.

The data collected in this study were formatted to allow vehicle emissions estimates using the International Vehicle Emissions Model (IVEM) (Davis et al., 2005). Using the IVEM emissions per km were estimated for each vehicle category and fuel type. Then total annual vehicle kilometer traveled for each vehicle category is multiplied to get the total emissions for each category and then those numbers were summed to get the annual total emissions for the metropolitan city of Istanbul. The developed road transport emission inventory was used in a recent study (Elbir et al., 2010).

Maritime. Maritime sector emissions were calculated for internal ferry lines and international cargo shipping (Table 1). Fuel consumption for 9 major ferry operating routes was obtained from the Istanbul Fast Ferries Co. Inc. (IDO) for the year 2007. The majority of these vessels are equipped with high speed engines (Deniz and Durmusoglu, 2008) and their emissions were calculated by employing the emission factors of EMEP/CORINAIR (2001). Only cruising emissions were taken into account.

The quantification of international cargo shipping emissions was based on the monthly vessel (categorized in 8 vessel types) traffic in the Marmara Sea and the Bosporus crossing for the year 2007 (see the SM, Table S3). Annual traffic data in the port of Ambarli were also available (Kilic, 2006). In order to calculate the emissions the vessels were grouped according to their engine type. The split was based on the 2003 world fleet statistics provided by Deniz and Durmusoglu (2008). Consequently, 2% of the vessels are equipped with high speed diesel engines, 32% are equipped with medium speed diesel engines and 66% are equipped with slow speed diesel engines while gas turbines and steam engines have a minimal share in the world fleet and were not taken into consideration. The emissions during the cruising mode as well as emissions during the hoteling and the maneu–vering phases were also quantified. The emission factors used for the aforesaid operating modes for all pollutants in question are those from Trozzi and Vaccaro (1998) and Cooper and Gustafsson (2004) (see the SM, Table S4). The emissions were calculated as the multiplication product of the relevant emission factors (per mass of fuel) and the fuel consumption per vessel type (Trozzi and Vaccaro, 1998) in each operating mode.

The engine power in each operating mode per vessel type as a proportion of the engine's full power was derived by USEPA (2000). The operating time in the hoteling phase was taken equal to 30 minutes (Deniz and Durmusoglu, 2008) and for the maneu–vering phase also equal to 30 minutes (Markakis et al., 2010b). The total cruising time was calculated using typical values for the cruising speed of each vessel type (Trozzi and Vaccaro, 1998; Deniz and Durmusoglu, 2008) and the distance travelled.

The cruising distance was extracted from the GIS database available and contains the cruising lines in the Marmara Sea and the Bosporus crossing. In order to calculate the distance the vessels were classified into transit and non transit ships. A transit vessel passes through the Bosporus and Canakkale straits while cruising in the Marmara Sea in between the crossings. A non–transit ship also passes the Turkish Straits but calls at Marmara's ports (Ambarli, Tekirdag, Izmit, Haydarpasa and Bandirma being the largest) (Deniz and Durmusoglu, 2008) for loading/unloading operations. After the ship finishes port operations, she cruises in the Sea of Marmara. Thus, vessels that pass through the Bosporus crossing (56 606 in number) were assumed to cruise also in the Marmara Sea. The split into transit and non–transit vessels was taken from Deniz and Durmusoglu (2008) which utilized official data for the year 2003. Consequently, from the 56 606 cruisings in the Marmara Sea and cross the Bosporus strait, 61.7% were transit vessels (34 926 ships) and 38.3% were non–transit vessels (21 680 ships).

Solvents use and coal extraction. The emissions of NMVOCs from the use of solvents were quantified using population statistics provided at neighborhood level. The relevant per capita emission factors have been derived from USEPA (1995). The quantified emissions considered in this study are only those relevant to the domestic use of solvents. Other solvent related emission sources were not accounted for either due to lack of relevant statistical information (e.g. solvent quantities and specific solvent types consumed) or lack of knowledge on whereas a number of industrial related sources (metal degreasing, car manufacture etc.) are relevant for the area.

To quantify particle emissions from the coal extraction operations the quantities of the extracted coal in two major coal sites in the European side (located in Yenikoy and Ciftalan with a total annual extraction capacity of 750 kt of coal) were used (Mining companies, personal communication). The emission factors implemented (50 g t^{-1} coal extracted for PM_{10} and 5 g t^{-1} coal extracted for $PM_{2.5}$) were extracted by the online database of TNO/CEPMEIP (http://www.air.sk/tno/cepmeip/) and they were compiled based on the USEPA (1995) methodology for open cast mining.

2.4. Emissions derived from the TNO emission database

The inventory of TNO was compiled by the Netherlands Organization (TNO) and it was originally prepared for the GEMS project (Hollingsworth et al., 2008) for the reference year of 2003 with a grid spacing of 1/8 by 1/16 degrees, longitude/latitude (approximately 7 x 7 km). It is based on official emission data on a country basis that has been submitted to EMEP/CLRTAP (Wagner et al., 2005). The inventory covers the European territory and a part of West Asia. For the needs of this work a portion of it was extracted to cover the GIA. The general performance of the emission inventory of TNO as regards the emissions of NO_x in Europe can be found in a recent study (Huijnen et al., 2010).

The emission inventory of TNO was compiled using activity data from a number of sources, different emission factor databases as well as methodologies some of which are summarized below. The particle emissions for all sectors were calculated in the framework of the TNO/CEPMEIP project which aimed to produce national estimates for a number of European and non–European countries. The activity statistics originate from a large variety of sources which are documented in the project online emission database. The emission factors (with references) are also included in the website.

The emissions from each macrosector are comprised from a number of individual emission sources. The industrial activities covered are those from primary and secondary iron and steel plants, primary and secondary non–ferrous metal smelters, cement factories, chemical plants and fertilizer manufacture plants and are calculated (except from particulate matter) from activity statistics (annual quantity of material produced) derived from the IIASA RAINS emission model (available at http://gains.iiasa.ac.at/gains/). The emission factors used are developed under the LOTOS/EDGAR emission inventory and documented in Olivier et al. (2001) for each industrial sector. The other mobile sources and machinery sector (railway transport, agriculture and industrial machinery) emissions are calculated based on fuel consumption data (different fuel types are taken into account) and originate from the International Energy Agency (IEA, 2003). The emission factors were derived from Olivier et al. (2001). Both the activity information and the emission factors used for the quantification of the waste treatment and disposal sector originate from the LOTOS/EDGAR emission inventory (Olivier et al., 2001). Finally the agricultural sector emissions are quantified based on the production of nitrogen fertilizer (for the fertilizer application emissions) derived from the International Fertilizer Manufacturing Association (IFA, 2002) as well as animal statistics (for the animal related emissions) derived from the Agriculture Statistical Database (FAOSTAT, 2003). For the former subsector the emission factors of the IIASA RAINS emission model and for the latter subsector the emission factors of the CORINAIR handbook (EMEP/CORINAIR 2001) were used. The spatial allocation of emissions is based either on population density (CIESIN, 2001) or on the PELINDA landcover database (De Boer et al., 2000).

2.5. Emissions of the aviation sector

Ataturk international airport emissions were taken from the study of Kesgin (2006). Kesgin (2006) used a calculation model to estimate landing and take–off operation emissions that are based on flight data recordings taken by the State Airports Authority and include type and number of aircrafts, number of passengers, amount of cargo and fuel consumptions. A thorough analysis of the aviation emissions is found in Kesgin (2006) and references therein.

3. Results and Discussion

The annual emission estimates for the aggregated pollutant groups of CO, NO_x, SO_x, NMVOC, NH_3, PM_{10} and $PM_{2.5}$ for each source category are presented in Table 2. The table clearly shows that road transport plays the main role among all other sectors. Road transport, alone, is responsible for 83% and 79% of CO and NO_x emissions respectively. Note that gasoline vehicles make a significant contribution (75% of CO and 57% for NO_x road sector emissions) due to vast amount of passenger vehicles in Istanbul (1.6 million as of 2006 and 800 new vehicles enter traffic daily). Solvent use contributes with almost 30% of the total NMVOC emissions while the waste treatment sector also has a significant contribution with 20%. Only the Ambarli power plant produces nearly 36% of the total calculated SO_x emissions in the area as it uses high sulfur content (3.0%) heavy fuel oil. The second largest share of SO_x emissions stem from the industrial combustion sector which accounts for 23% of the total SO_x with almost the entire amount originating from the combustion of coal.

The emissions from cargo shipping contribute with 8.9% to the overall NO_x emissions in the area, while 17.3% of the SO_x emissions are produced from the same source. Table 3 tabulates the emissions calculated in the area per vessel type. The majority of NO_x emissions originate from the general cargo vessels (45.2%) which hold the largest share in the fleet. Tankers are the second largest contributor of NO_x emissions (22.9%). From the total emissions of NO_x inside the study's domain about one third is emitted inside the straits of Bosporus. Note that a considerable amount of cargo shipping emissions is missing from the part of the study domain that covers the Black sea due to lack of the travelling routes in that area.

Figure 3a illustrates the spatial distribution of CO emissions from the residential heating category, Figure 3b, SO_x emissions from the industrial combustion category and Figure 3c NO_x emissions from the road transport sector. In Figure 3a, it is clearly

Table 2. *Sectoral emission totals (in t yr^{-1}) for all pollutants considered in the GIA*

Source category	CO	NO_X	SO_x	NMVOC	NH_3	PM_{10}	$PM_{2.5}$
Combustion Residential	47 399	6 513	13 369	2 011		4 286	4 273
Combustion Industrial	1 741	7 123	21 020	88		29 796	8 709
Processes Industrial	14 352	211		273		9 605	7 354
Distribution of fossil fuels			2 121	–			
Coal extraction				–		38	4
Solvents Use				23 000	3 256		
Road Transport	363 252	241 895	2 124	34 661		10 533	10 533
Off–road vehicles/machinery [a]	51	1 233	1 273	301		2 268	2 148
Aviation	2 792	1 600	85	541			
Local ferries	174	2 009	273	32		79	79
Cargo Shipping	1 199	27 050	15 686	464	9	1 822	1 822
Waste treatment & disposal	3 173			15 764		1 047	1 047
Energy	3 187	9 880	32 316	154		1 088	809
Agriculture	34	7 195	2 415	8	3 249	100	22
Totals	**437 354**	**304 709**	**90 682**	**77 297**	**6 514**	**60 662**	**36 800**

[a] *Includes emissions from off–road machinery and the Ataturk international airport.*

Table 3. *Emissions of cargo vessels (in t yr^{-1}) for all pollutants considered in the study domain*

Vessel type	**CO**	**NO_x**	**SO_x**	**NMVOCs**	**$PM_{10}/PM_{2.5}$**
Tankers	265	6 184	3 572	103	411
Containers	121	2 771	1 583	47	183
RoRo	12	204	120	4	14
LPG	23	433	253	8	29
Bulk Carriers	128	2 889	1 678	50	196
General cargo	540	12 228	7 118	211	831
Passenger	74	1 600	931	28	109
Other	36	741	431	13	50
Total	1 199	27 050	15 701	464	1 825

seen that CO emissions (almost entirely from the combustion of coal) from residential heating, originate from the two coastal sides of the Bosporus strait, where most of the population inhabits. The old centers of the city at the European side (blue circe) and Kadikoy region (red circle) on the Asian side are where the main and the oldest residential areas are located. Additionally, the traffic emissions are also high around those two city centers (Figure 3c). The majority of SO_x emissions originate from the industrial activities which are present only in the organized industrial areas. The highest rate of emission comes from the Ikitelli industrial region which hosts the highest amount of industrial complexes in the city (10 kt yr^{-1}).

The monthly variations of all pollutants are illustrated in Figure 4. The expected trend of CO emissions is a result of the residential combustion although the most important emission source is by far the road transport sector. The seasonality of emissions from residential heating is especially clear, showing a maximum during wintertime (November to February) and a minimum during summer time. SO_x emissions show the same annual variation. In contrast, NO_x emissions variation is influenced by the road transport sector during summertime. Interestingly, a clear peak in NO_x emissions is observed in October as a result of the emission rise primarily of the agriculture sector and secondly by the road transport and the residential sectors. PM_{10} emissions variation is influenced by the industrial combustion sector which peak during wintertime. The peak values are observed in February and March as a result of both the road transport and the industrial combustion sectors emissions. $PM_{2.5}$ emissions variation is similar to the PM_{10} but showing a less pronounced seasonality as a result of the much higher share of the road transport emissions in $PM_{2.5}$ which also presents weak seasonality.

The variation of weekly emissions is calculated to be less than 1.5% during the weekdays, while emissions drop during weekends due to the reduced anthropogenic activity. The reduction of CO by 15.3% and fine particles by 16% is attributed to road transport (for which emissions drop about 15% for both pollutants). For the SO_x emissions the weekend reduction by 13.3% is a result of the reduc–tion in the industrial sector (for which emissions drop about 25% on weekends). The residential combustion sector as expected presents a constant variation through the week.

The diurnal variations of all pollutants in question for a typical weekday in January are illustrated in Figure 5. As expected, the rush hours clearly affect the emissions trends in the area. The variation trends fit with the social habits: the emissions of CO, NO_x and particles reach the maximum levels in the morning hours (6:00–7:00 local time), along with the beginning of traffic. SO_x emissions morning peak is a result of the central heating opera–tions. The second maximum in CO, NO_x and particles is observed in the evening hours (15:00–16:00 local time), together with the increase of traffic. The latter maximum in traffic, which is con–nected with the returning of people from their work, precedes the peak in SO_x emissions as a result of central space heating activities. The almost constant emissions of NMVOCs throughout the day are a result of their influence by the solvent use and the waste treatment sectors which show a small diurnal variation.

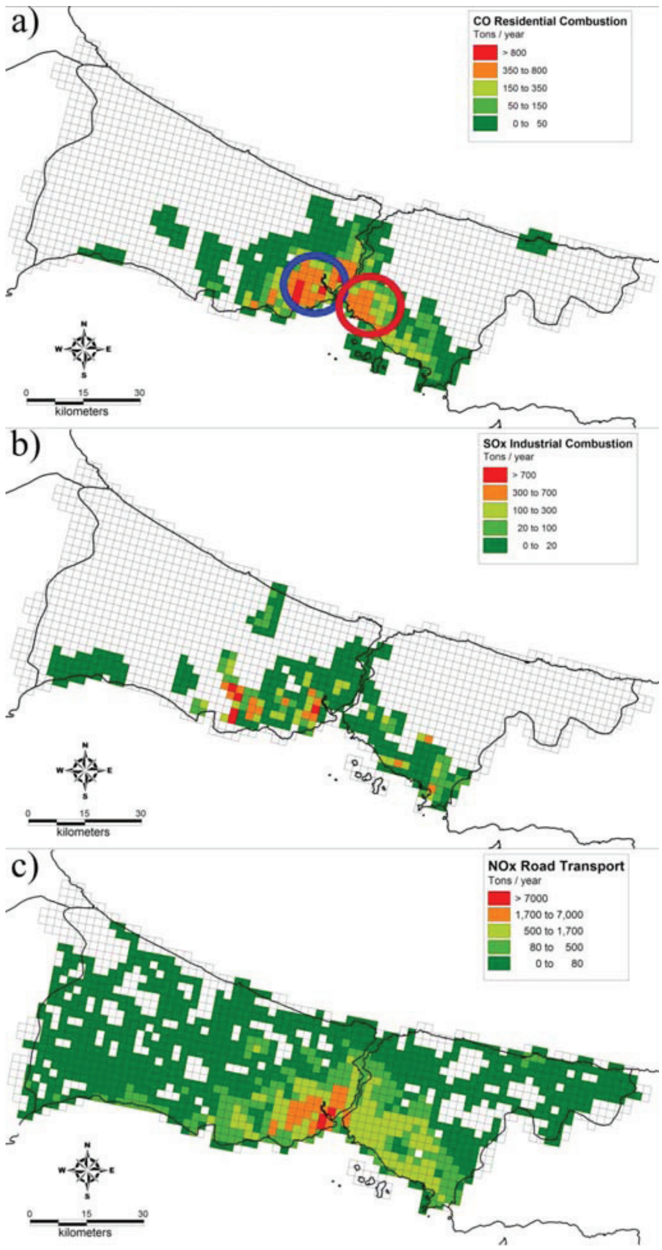

Figure 3. *Spatial distribution of* ***(a)*** *CO emissions from the residential heating sector* ***(b)*** *SO_x emissions from the industrial combustion sector* ***(c)*** *NO_x emissions from the road transport sector.*

Finally Figure 6 depicts the emissions of particulate matter (Figure 6a) and NMVOCs (Figure 6b) per chemical specie. Consequently particulate matter (PM_{10} and $PM_{2.5}$) is primarily emitted as "other particles" (56% and 48% respectively) with the combustion of coal in the industrial sector and the industrial processes to be the main contributor. The group characterized as "other particles" includes various trace elements and other unidentified materials of anthropogenic origin. The industrial sector is also the dominant emitter of the elemental carbon (EC) fraction of PM_{10} while the road transport sector is the main emitter of the elemental carbon and the organic carbon fraction of $PM_{2.5}$. The EC fraction of 0.2 for $PM_{2.5}$ in this study is consistent with the $PM_{2.5}$ EC fraction of 0.24 reported in Schaap et al. (2004). The profiles in Schaap et al. (2004) originate from the study of Streets et al. (2004) which presents a black carbon (BC) emission inventory for China. The BC profiles used in Streets et al. (2001) are

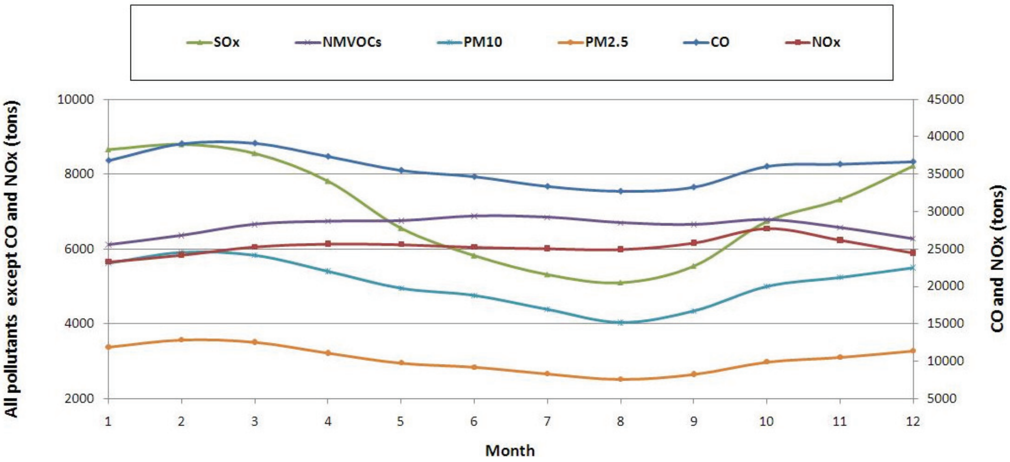

Figure 4. *Monthly variation of emissions in the study domain.*

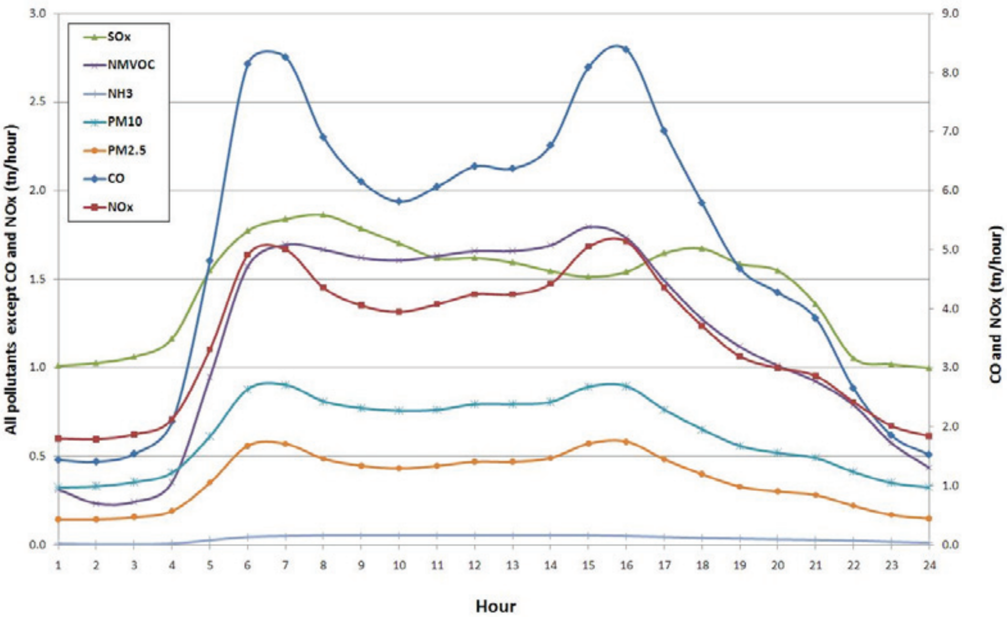

Figure 5. *Diurnal variation of emissions for a typical weekday of January in the study domain.*

consistent with Europe since they are almost exclusively based on western technology (Schaap et al., 2004). The use of solvents and the road transport sectors are responsible for the three most contributing NMVOCs species/groups of species which are the higher alkanes and aromatics (21.4%) toluene (8.7%) and xylenes (6.4%). Acids (5.1%) are produced by the waste treatment and disposal sector.

4. Evaluation of the Emissions Inventory

4.1. Data limitations and uncertainties

This study presents an emission inventory that has been compiled using the most updated activity data for the calculation of residential and industrial combustion, the energy sector, the maritime sector, solvents use and coal extraction emissions employing a bottom–up methodology. Moreover the emission data that were extracted from TNO, to fill for the remaining sources, were spatially allocated using high quality geographical information to compile spatial indicators which correlates the emission source with its geographical activity level, using GIS technology. Nevertheless, the presented data are subject to limitations. The most important are identified and discussed below.

Regarding the quantification of combustion emissions there are two sources of uncertainty. These are the inherent uncertainty of the emission factors as well as the selection of representative emission factors for the area. It should be noted that apart from the road transport sector there are no specifically developed emission factors for other sources and pollutants in the region. The quality ratings of all the emission factors used for the calculation of fuel combustion emissions in this study are tabulated in Table S2 (see the SM). In addition, the uncertainty, which is connected with the proper selection of the emission factors, is due to limitations in the provided data. For instance, there was no information regarding the share of smaller and larger boilers in the industries, the control efficiency implemented, and the firing technique used for the boilers (normal firing, tangential firing etc.) or the boiler type. In this study the uncontrolled emission factors for PM were used. Large industrial units equipped with modern abatement technology such as ESP filters are expected to have a reduced emission rate of more than 80%.

The on–road traffic emissions may introduce large uncertainties. On–road emissions were obtained from the study conducted by EMBARQ and Istanbul Metropolitan Municipality. Although the study was the first effort in measuring emissions under real–world conditions in Istanbul traffic, only 140 vehicles

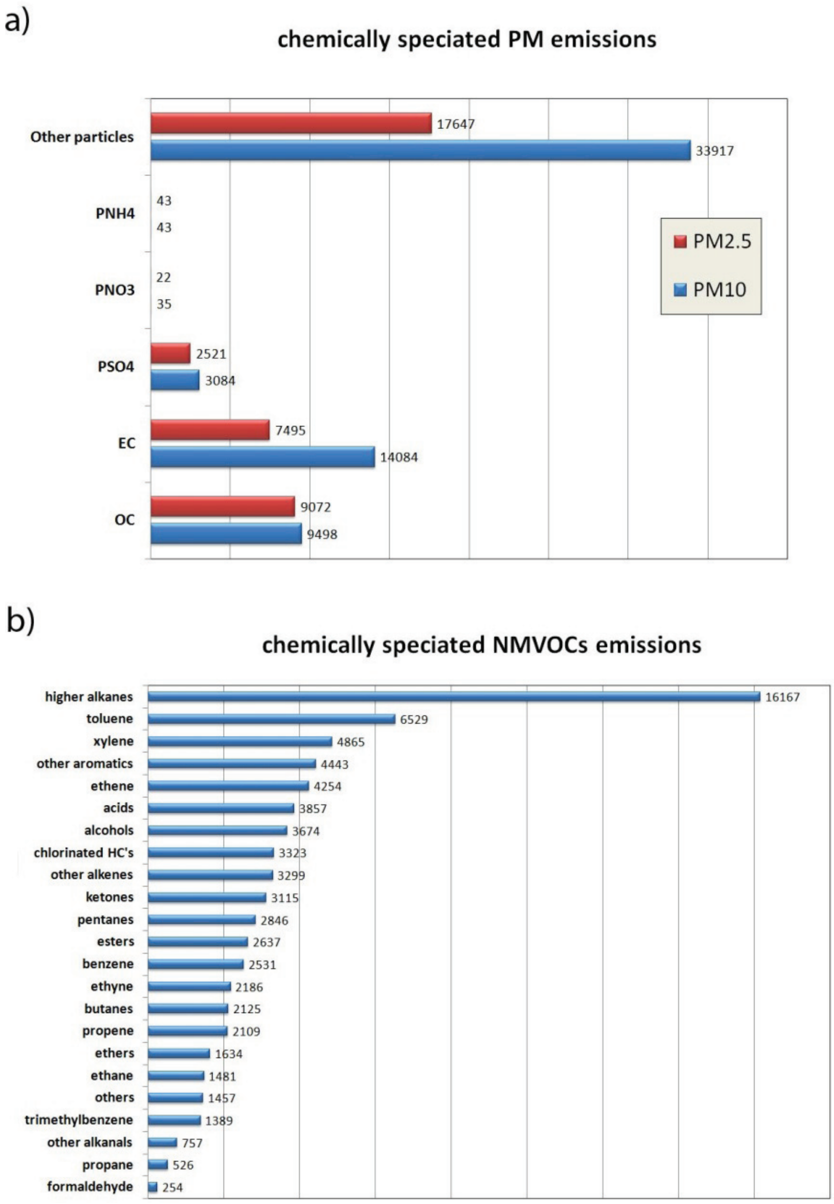

Figure 6. *Chemical speciated emissions (in t) of* ***(a)*** *particulate matter and* ***(b)*** *NMVOCs.*

were tested. The uncertainty can be significantly reduced if more vehicles can be tested. Another important source of uncertainty in the final estimates originates from the heavy–duty trucks due to lack of information on the annual activity of these vehicles within the city boundaries. In this study emission factors are measured under real–world conditions using on–board instruments therefore the emission factors are significantly higher than the ones pre–sented in COPERT or EPA's MOBILE6 (not higher than EPA's MOVES model, since they use a similar approach) as they use laboratory based measurements and average speed correction methods whereas this study used real–world driving with power demand approach (like MOVES). Therefore, higher vehicle emissions are expected. On top of that, the fleet selected for the emission inventory represents the actual fleet and it is not based on theoretical values. For example, an in–use Euro IV bus' emissions are significantly higher than a new Euro IV bus because of maintenance issues. The fuel quality used is also a factor that significantly increases the PM levels from buses (they are operating on 1 000 ppm or higher sulfur). Nevertheless instrumented vehicles were used to collect activity data. The level of uncertainty can also be reduced if more activity data can be collected on different roadways. Finally, an additional uncertainty was introduced when distributing the emissions estimated spatially. Detailed information on vehicle distribution as well as driving conditions at every roadway link can be utilized to improve the accuracy of the estimates. Although it is expected that uncer–tainties are present we have to note that this is the first effort to compile localized emission factors for traffic that correspond not only to the characteristics of the Istanbul's fleet but also to the local driving behavior and conditions. These emission factors are considered more reliable than EPA's emission factors which are often arbitrarily been used to describe emissions for Asian or Eastern European counties in the absence of other datasets.

In addition, the evaporative emissions of NMVOCs from the road transport sector are missing from the inventory as well as the use of solvent from a number of industrial sources such as metal degreasing and paint applications. Additionally it has to be taken into account that the per capita emission factors used to quantify the solvents use emissions, instead of the usage of source–specific solvent consumption amounts, can lead to high uncertainties.

The uncertainties in the quantification of the maritime sector and in particular the cargo shipping emissions are mainly associated with the use of average daily consumption of fuel per vessel type. This approach, though, is widely used in the literature (Kesgin and Vardar, 2001; Endresen et al., 2003; Deniz and Durmusoglu, 2008) as the assembly of detailed data for individual vessels of the fleet is extremely difficult.

SO_x emissions from the production processes are expected to be underestimated. The annual amount, which was used in this study originating from TNO, is not considered representative for the area as it is in the order of a few tons per year. Other studies have indicated the importance of the metal industry as a large source of SO_x (Pham et al., 2008). Moreover the calculated rates of SO_x from the residential sector are expected to be lower than the real ones. The reason for this is the large amounts of low quality (high sulfur content) unauthorized coal mostly used in the outer parts of the city center where the least developed areas are located. The use of unauthorized, low quality coal was also reported by Cetin et al. (2007) which compiled an emission inventory for the nearby Kocaeli region.

4.2. Comparison with other emission studies and databases

The EMEP cells (in 50 km grid spacing) which cover the city of Istanbul were extracted from the on–line database (Vestreng et al., 2006) (available at http://www.ceip.at/emission–data–webdab/emissions–used–in–emep–models/) for 2003 in order to compare with the land emissions of TNO also representative for 2003. The comparison shows (Table 4) that generally TNO provides higher emissions than EMEP for all pollutants except for particles which are about 30% less in TNO (this discrepancy is attributed to the energy sector and residential sector emissions).

Table 4. *Comparison of the total annual emissions (in t yr^{-1}) with other databases*

Pollutant	TNO (2003)	EMEP (2003)	EMEP (2007)	This study
CO	221 875	144 308	102 790	435 981
NO_x	69 522	34 855	34 730	275 650
SO_x	104 231	20 218	23 000	74 722
NMVOCs	95 685	33 928	37 805	76 801
NH_3	7 266	22	22.8	6 505
PM_{10}	33 022	46 631	40 300	58 761
$PM_{2.5}$	23 520	34 898	31 128	34 899

The comparison between the 2007 EMEP emissions and this study reveals that the emissions compiled in this study highly exceed the emissions of EMEP. Except from $PM_{2.5}$ emissions which are comparable, presenting only a 12% difference, CO emissions are calculated to be 4.2 times higher than EMEP, whereas NO_x emissions exceed EMEP emissions by 7.9 times, SO_x emissions 3.2 times, NMVOC emissions 2 times, NH_3 emissions more than 2 orders of magnitude, and PM_{10} by 1.5 times (Table 4). This large discrepancy is a result of the road transport sector which in the present study exceeds 8.4 and 20 times the emissions of EMEP for CO and NO_x respectively whereas for NMVOCs the difference reaches 4.3 times. On the contrary the difference in the emissions of SO_x is caused by the combustion emissions in the energy, the residential and the industrial sectors (66 705 tons in this study to 21 995 tons in EMEP). The divergence in the emissions of PM_{10} is a product of both the road transport sector (3.6 times more) as well as of the industrial combustion sector (3.6 times more) whereas in $PM_{2.5}$ primarily of the road transport sector (4.5 times more). The closest difference in the emissions of particulate matter compared to the other pollutants is caused by the higher emissions of EMEP in the energy and the residential combustion sectors.

It has to be taken into account that the provided emissions for Turkey in the EMEP database were not compiled based on activity information but they are merely an estimation of the EMEP expert panel, provided that Turkey is not obliged to report its national emissions to EMEP as the European Union countries do. Conse–quently the emissions of the EMEP database for Turkey are highly questionable and uncertain and the large observed discrepancies can be result of the above mentioned. The procedures of the expert panel which are adopted for the emission estimation are not known and thus further discussion regarding those differences is not possible.

The comparison of the emissions of this study with the emissions database of TNO presents much lower discrepancies than those on the EMEP database except particulate matter. It must be noted that a portion of the differences is attributed to the reference years amid the studies. Consequently the emissions of NMVOCs are quite close (10.4% difference). CO, NO_x, PM_{10} and $PM_{2.5}$ emissions are 1.8, 1.5, 2 and 4 times higher respectively than the findings of TNO mainly due to the road transport sector. At this point we must emphasize the significance of utilizing area–specific emission factors which reflect both the circulating fleet and the driving conditions in Istanbul (EMBARQ, 2007). In contrast the road transport sector in the TNO database (and possibly in the EMEP database) was compiled utilizing the European emission factors (EMEP/CORINAIR 2001) which correspond to the EURO vehicle classification adopted within the European Union and there are inappropriate to represent the local situation in Istanbul. SO_x present lower emissions in our quantification (by 30%) mainly due to the industrial combustion sector (3 times more in TNO). This is probably attributed to the fact that a large portion of the industrial combustion emissions calculated in national level in TNO are spatially distributed with population density which results in an overestimation of the allocated amounts in Istanbul in which more than 20% of the country's population is located (the sulfur content of coal used in TNO is in accordance with the sulfur content used in this study).

Finally, the shipping emissions calculated in this study are compared with the findings of Deniz and Durmusoglu (2008) and the shipping database of EMEP. Deniz and Durmusoglu (2008) calculated the total emissions from the Marmara Sea and Bosporus strait covering international shipping and local ferries, as well as the shipping emissions from the Canakkale strait. The results show that the emissions calculated in this study were lower than the emissions from Deniz and Durmusoglu (2008), except for the PM_{10} emissions. CO emissions of this study are 2.9 times lower than the findings of Deniz and Durmusoglu (2008), whereas SO_x emissions are 57% lower, and NMVOCs emissions are 2.4 times lower. The deviation of CO, SO_x and NMVOCs emissions is attributed to the much lower emission factors used in this study (especially for the slow speed engines which comprise 66% of the fleet) originating from Cooper and Gustafsson (2004) compared with the respective emission factors of Deniz and Durmusoglu (2008) originating from an older study by Trozzi and Vaccaro (1998). On the other hand, PM_{10} emissions of this study are 28% higher than those of Deniz and Durmusoglu (2008). Although the emission factors used amid the studies are similar for PM, the operating fleet in this study is larger by 20%. The comparisons with the EMEP emissions of 2007 shows that apart for CO and NMVOCs which in this study are calculated lower than those of EMEP by 29% and 19% respectively, NO_x emissions are 65%, SO_x 36%, PM_{10} 32% and $PM_{2.5}$ 39% higher than the emissions of the EMEP inventory.

It should be noted though that both the land and sea emissions comparison presented in Table 4 between this study and EMEP is not straightforward. The EMEP grid is coarse (50 km) and the differences in the grid projections introduces deviations. Also, the emissions of Deniz and Durmusoglu (2008) are not spatially disaggregated and to derive the comparison amounts an approximation based on the cruised distance was used.

5. Photochemical Modeling Studies

The presented high resolution emission inventory was employed in a number of case studies (Im et al., 2010; Im et al., 2011a; Im et al., 2011b). The motivation of these studies was to examine the PM_{10} and ozone levels respectively as well as the effects of anthropogenic emissions on these levels in Istanbul.

Particularly, Im et al. (2010) evaluated the anthropogenic emissions by coupling the meteorological mesoscale model WRF and the chemical transport model CMAQ (Byun and Schere, 2006; Foley et al., 2010), in order to simulate a winter episode in January 2008, dominated by local anthropogenic emissions. In addition to examining the PM_{10} mass, sulfate, nitrate and ammonium aerosol components have also been investigated, as well as their sensitivities to emission changes, for the first time in this study. The uncertainties originated from the emissions and the possible effects of these uncertainties on the model concentrations were also discussed in the paper.

The model produced PM_{10} concentrations that were comparable with the observations in terms of magnitude. Overall, it was concluded that the first results of the WRF/CMAQ modeling system provided significantly improved results for Istanbul, especially in terms of magnitude, when compared to earlier studies for the area. Kindap et al. (2006) estimated an order of magnitude lower PM_{10} concentrations using the 50 km resolution EMEP emissions. However, in Im et al. (2010), PM_{10} concentrations were underestimated on average by 10%. Besides the improvements in the anthropogenic emissions, more realistic results can also be attributed to the higher spatial resolution of the model (2 km) used in Im et al. (2010) compared to the previous modeling efforts (Kindap et al., 2006). A better representation of the meteorological fields in a higher spatial resolution may also lead to better results, particularly in terms of resolving small scale circulations like land–sea breezes.

Regarding the study of Im et al. (2011a) ground level ozone concentrations were simulated for Istanbul during a summer episode in June 2008, using for the first time known a high resolution modeling system that employs CMAQ chemistry and transport model offline–coupled with MM5 meteorological model. Mean ozone levels are well captured by the model with 10% overestimation at one station and 16% underestimation in another.

6. Conclusions

Emission inventories are a major source of error when trying to interpret air quality modeling results. An inventory must provide hourly, gridded and chemically splitted emissions for the chemistry and transport models. There are a number of studies for the estimation of emissions from particular sources for Istanbul but these inventories only provided the annual emissions from the whole domain. Thus, a high resolution emission inventory that is compiled for modeling studies has been the major deficiency for conducting such modeling studies for the region. The emission inventory presented in this paper has been compiled for the Greater Istanbul Area on 2 km horizontal resolution, including hourly emissions for 23 speciated NMVOCs and 16 gaseous/particulate species.

The results clearly indicated that road traffic is the dominant source category for most of the conventional pollutants such as CO, NO_x and NMVOCs. SO_x emissions are primarily produced by the combustion in the energy and the industrial sectors while the cargo shipping activities have also a significant contribution. PM_{10} main contributor is industry while fine particles are equally emitted by the industrial and the road transport sectors. The results suggest that an important air quality issue, PM pollution, may highly be influenced locally from the road transport emissions. Thus, air pollution reduction strategies should be developed and implemented considering the sectoral distributions of emissions.

The study also points out two major deficiencies for such studies in Turkey; the lack of emission factors, particularly produced for the local activities and the lack of temporal profiles. These parameters highly influence the estimations of emissions accurately.

This study aims to contribute to air quality modeling studies for Istanbul, as well as to fill a major gap in air quality studies for the area. Thus, employing this inventory as an input in a modeling study can help to understand the real accuracy of the inventory. In a recent modeling study, it was concluded that the presented emission inventory significantly improved the PM_{10} simulations for Istanbul, especially in terms of magnitude, when compared to earlier studies for the area. The comparisons with other emission inventories and the first simulations that employ our updated emissions clearly point that large scale simulations that covers the extended Istanbul area and use previous emission inventories can lead to large underestimations regarding both local and regional PM_{10} levels. Nonetheless, this study is a beginning to build up various data on emission activities for the Greater Istanbul Area.

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Supporting Material Available

Annual fuel consumption in the GIA (Table S1), Emission factors used for the quantification of residential and industrial combustion emissions (Table S2), Annual vessel traffic in the Bosporus crossing and the Ambarli port (Table S3), Emission factors (in $g\,t^{-1}$ of fuel) used for the quantification of cargo shipping emissions (Table S4). This information is available free of charge via the Internet at http://www.atmospolres.com.

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