

Comparison of predicted and observed PM₁₀ concentrations in several urban street canyons

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Abstract This paper presents an evaluation of a street canyon model (Operational Street Pollution Model) in several urban streets having different configurations. The model was performed for the prediction of particulate matter (PM₁₀) concentrations from exhaust emissions of mobile sources in five street canyons in the city of Izmir, Turkey. Hourly concentrations of PM₁₀ were observed at the streets and the relevant hourly meteorological parameters were measured at the roof level. The hourly street level measurements by a mobile ambient air quality monitoring station and on-site automatic traffic counts were conducted for 1 week in each street during the period of November 2007 and March 2008. The urban background concentrations were also obtained from four stationary air quality monitoring stations in the city during the measurement campaigns and they were included in the modeling studies as the contribution of background air quality. Finally, statistical analyses were carried out to evaluate the model performance by comparing the predicted and observed time series of PM₁₀ concentrations using a correlation coefficient and an index of agreement (IA). The IA varied from 0.87 to 0.98 at the symmetric canyons and the correlation coefficient ranged from 0.68 to 0.92, indicating modeling performances ranging from acceptable to very good. The similar values were calculated between 0.74 and 0.76 for IA and between 0.34 and 0.41 for correlation coefficient at the asymmetric canyons. The best agreement between predicted and observed PM₁₀ concentrations (IA=0.98, $R^2=0.92$) was found for Cumhuriyet Avenue in this study. These values are found as the best agreement in overall studies in literature.

Keywords OSPM · Street canyon · PM₁₀ · Traffic pollution · Dispersion modeling · Izmir

Introduction

The street canyon environment has been pointed out as a “hot spot” in terms of air pollution since traffic is the major pollutant source sector in the biggest cities. As a consequence, many recent studies have focused on the modeling and monitoring of air quality in urban street canyons (Hirtl and Baumann-Stanzer 2007; Ketzler et al. 2007; Vardoulakis et al. 2007; Assael et al. 2008; Berkowicz et al. 2008; Zhou and Levy 2008; Murena et al. 2009; Taseiko et al. 2009).

Various street canyon models have been developed to evaluate the impact of traffic emissions in street canyons. These models can be categorized as more sophisticated numerical modeling tools, such as Computational Fluid Dynamics (CFD) models or as simpler parametric modeling tools (Operational Street Pollution Model [OSPM], STREET, CPBM, etc.). Numerical CFD models need many parameters to describe street canyons, high spatial resolutions such as a few meters, more computer power, and more time to complete calculations in comparison to simpler parametric models (Vardoulakis et al. 2003; Berkowicz et al. 2008; Assael et al. 2008; Murena et al. 2009).

The parametric models are widely used to estimate the concentrations of various pollutants in street canyons. These models are based on the characteristics of flow conditions, street geometry, and meteorological conditions in a street. Pollution levels in a street are calculated using traffic emissions in this particular street only, while contributions from the surrounding streets and other sources are treated as background pollution. These models approach

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that transport and dispersion of pollutants in the streets are generally modeled by a combination of a plume and a box model. The parametric models are based on a number of empirical assumptions and parameters that might not be applicable to all urban environments. The knowledge indicates that they are generally recalibrated with a small number of field measurements, if they are to be applied to new locations (Vardoulakis et al. 2003).

The parametric street canyon models used for the estimation of the pollutants are quite successful in predicting average concentrations in the streets. Several previous studies focused on the evaluation of modeling performance for different gaseous pollutants only (i.e., NO, NO₂, and CO; Kukkonen et al. 2000; Ziv et al. 2002; Aquilina and Micallef 2004; Gokhale et al. 2005; Berkowicz et al. 2006; Solazzo et al. 2007; Berkowicz et al. 2008), particulate matter only (i.e., PM₁₀ and PM_{2.5}; Bihan et al. 2002; Ketzal et al. 2007; Assael et al. 2008), or both gaseous pollutants and PM together (Mensink et al. 2006; Vardoulakis et al. 2007; Zhou and Levy 2008). The results of the statistical analysis for model performance in the previous studies indicate that the agreement between observed and predicted concentrations is generally better for gaseous pollutants than particulate matter.

The studies mentioned above estimate generally air pollutant concentrations in a single street. In the present study, a widely used street canyon model was used to predict PM₁₀ concentrations in five main streets having different configurations in the city of Izmir, Turkey. Model input requirements, underlying assumptions, and model performance were also discussed.

Methodology

The model

The Danish Operational Street Pollution Model (WinOSPM version 5.0) developed by the National Environmental Research Institute in Denmark (Berkowicz 2000) was used for traffic pollution modeling in street canyons in this study. OSPM is a simple parameterized dispersion model based on a combination of a Gaussian plume model for direct contribution from the street traffic, a box model for the recirculation part of pollutants, and a simple chemical model for three species: NO, NO₂, and O₃ (Berkowicz 2000). Deduction for parameterization of flow and dispersion conditions in streets is based on the extensive analysis of experimental data and model tests. OSPM assumes that both the traffic density and exhaust emissions are uniformly distributed across the canyon. The turbulence in the street is assumed to be composed of two parts: a part dependent on wind speed and a part due to traffic-induced turbulence (Berkowicz et al. 2008).

OSPM requires traffic flow, either as hourly values or as average daily variation, emissions calculated from the traffic volume- and the vehicle speed-dependent emission factors, urban background concentrations, street geometry, and meteorological data above roof level (i.e., wind speed and direction). Temperature and global radiation are also other meteorological parameters needed for the calculation of NO₂ concentrations. The latest Windows version of OSPM (WinOSPM) contains a fully integrated emission module based on the COPERT methodology (Gkatzoflias et al. 2007). This module allows the users to define specific emission factors according to travel speed and vehicle fleet in the different technology and legislation categories. A detailed discussion of the OSPM concept can be found elsewhere (Berkowicz 2000; Berkowicz et al. 2008).

The site and sampling program

The data used in this study originates from five main streets in Izmir, Turkey. The city of Izmir is located in the western part of Turkey in the coordinates of 26°52' and 27°19' East longitudes and 38°19' and 38°32' North latitudes with an urban extension of 50 km×50 km. The city is the third biggest urban agglomeration in Turkey with 3.4 million population and covering a total area of 12,012 km² (Turkish Statistical Institute (TUIK) 2008). The region is mostly classified within the local climate of the Mediterranean Sea, but actually, the region tends to the semi-arid climate. The annual rainfall was 456 mm, while highest monthly rainfall was 144 mm during May 2007. December was the coolest month with a daily average temperature of 9°C, while in July, the daily average reached to 30°C for the year 2007. The maximum hourly average temperature in the city was 40.5°C, while the minimum hourly temperature was 0.8°C. The annual mean wind speed was 2.6 m/s, while the predominant wind directions were W, SSE, and SE (with frequencies of 34%, 13%, and 10%, respectively) for the year 2007. The city has sizeable economic activities and hosts many industries that are emitting high quantities of air pollutants. Traffic was shown to be one of the most important pollutant source categories in the city (Elbir 2003; Elbir and Muezzinoglu 2004).

Five main street canyons (Girne Avenue, Mustafa Kemal Street, Cumhuriyet Avenue, Mithatpasa Avenue, and Inonu Street) located in the city center were selected for the present study. The selected street canyons are representative of the general traffic flow in the city. They have typical geometrical configurations. The streets are approximately 25–30 m wide with buildings 20–25 m high on both sides, except Inonu and Mustafa Kemal streets. These two streets were asymmetric canyons because buildings that are flanking the streets do not have the same heights. Details of the street geometry for the five street canyons are given

in Table 1. A map of the city showing the locations of the five streets studied is given in Fig. 1.

Hourly ambient air quality measurements and vehicle counts in the street canyons were conducted during the period of November 2007 and March 2008. Table 1 shows the sampling periods for each street canyon. All traffic data in the street canyons were obtained from an automatic traffic counting system, MetroCount Vehicle Classifier System (by MetroCount®; <http://www.metrocount.com>). This system includes a pneumatic rubber tube sensing method that counts the axes of the vehicles, classifies the vehicles, and determines the speeds of the vehicles. The types of vehicles categorized in the study were motorcycles, passenger cars, vans, and busses/trucks.

A mobile air quality monitoring station was located in each of the five street canyons for about a week (Table 1). The station was located adjacent to the street canyons and between 5 and 10 m from the nearest traffic lanes. Table 1 shows the location of the station in each street with respect to wind direction. Hourly PM₁₀ concentrations were measured using a PM₁₀ sampler (Model FH62-C14, Thermo Scientific®; <http://www.thermo.com>). The sampler was calibrated before operation in a new street after a measurement campaign in the previous street was completed. The measurement height was 3 m above the ground (as the PM₁₀ sampler inlet probe) in all streets. The hourly values for temperature, wind speed, and wind direction were also obtained from a telescopic tower located in the mobile station. The meteorological parameters were measured at the street roof levels as required by the OSPM raising the tower up to the roof level of each street.

As done in many researches (Wang and Xie 2009; Assael et al. 2008; Neofytou et al. 2008; Ghenu et al. 2008; Gokhale et al. 2005), the hourly measurement values observed in the stationary stations of the ambient air quality monitoring network in the city center were applied as background concentrations. Four stationary ambient air quality monitoring stations (Bornova, Guzelyali, Karsiyaka, and Alsancak) were used to represent the hourly back-

ground PM₁₀ concentrations in the streets. These monitoring stations are around a few kilometers away from major streets in the city center. The stations are not located in any street in the city. It is assumed that the measurements at these stations are not directly affected from the pollution of any street. Urban background concentrations were used as the contribution from the surrounding streets and other sources treated as background pollution in the modeling studies. The locations of the urban background stations are shown in Fig. 1.

In the study, the direct exhaust emissions were estimated by the COPERT methodology in the street canyons. This methodology involves the use of specific CORINAIR emission factors according to travel speed and vehicle fleet in the different technology and legislation categories (European Environment Agency (EEA) 2007). Other emission sources such as wear of brakes and clutches and emissions from road abrasion, tire wear, and road dust resuspension were assumed as negligible in this study, although several studies indicate that non-exhaust emissions are more important than the exhaust emissions in some European countries (Ketzler et al. 2007). The largest contribution to particulate matter concentrations in the street canyons generally belongs to road dust resuspension (Manoli et al. 2002). In this study, measurement campaigns were generally performed in a wet period (between November and March), so the source of road dust resuspension was not included. Besides, all the streets studied are covered with asphalt and they are regularly cleaned by mechanical street sweepers. The use of street sweeping is a way to reduce the emissions of particulate matter from pave roads (Norman and Johansson 2006). Finally, the vehicles never use studded tires in the city due to the climate of the region (Mediterranean).

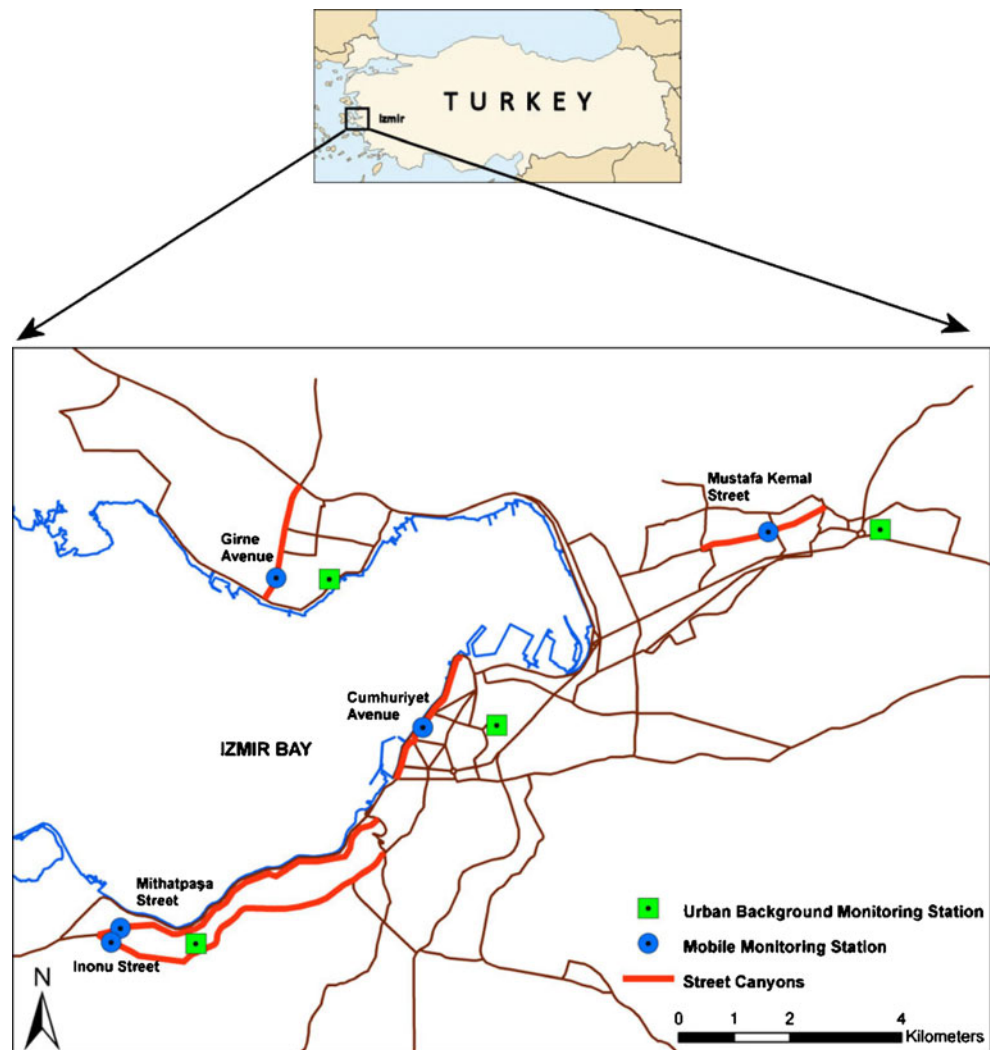
Model evaluation

Three statistical parameters were used for the evaluation of model performance: the index of agreement (IA), the correlation coefficient of determination (R^2), and the

Table 1 Characteristics of street canyons and the measurement periods

Street name	Location of station	Windward average building height	Leeward average building height	Average street width	Ratio (height/width)	Angle (from the north)	Measurement period
Mustafa Kemal Street	Windward	10	20	30	0.67	75	5–11 November 2007
Cumhuriyet Avenue	Leeward	25	25	35	0.71	30	24–30 December 2007
Girne Avenue	Leeward	27	27	30	0.90	10	21–27 January 2008
Mithatpasa Street	Windward	20	20	30	0.67	80	18–24 February 2008
Inonu Street	Windward	10	30	30	1.00	120	3–9 March 2008

Fig. 1 Location of street canyons, mobile monitoring station in street canyons, and urban background stations in the city



fractional bias (FB). The IA is a measure of how well the model represents the pattern of perturbation about the mean value. It can vary from 0 (theoretical minimum) to 1.0 (perfect agreement between the observed and predicted values). On the other hand, FB represents a measure of the agreement between the mean predicted and observed values and hence perfect agreement between two data sets is indicated when it equals to 0. More information about these statistical methods can be found elsewhere (Kukkonen et al. 2000; Elbir 2003). Three main statistical parameters calculated in this study are defined as follows: The IA:

$$IA = 1 - \frac{\sum_{i=1}^N (P_i - O_i)^2}{\sum_{i=1}^N (|P_i - O| + |O_i - O|)^2} \quad (1)$$

where N is the number of data, P_i is the model prediction, O_i is the observed concentration, O is the mean value of

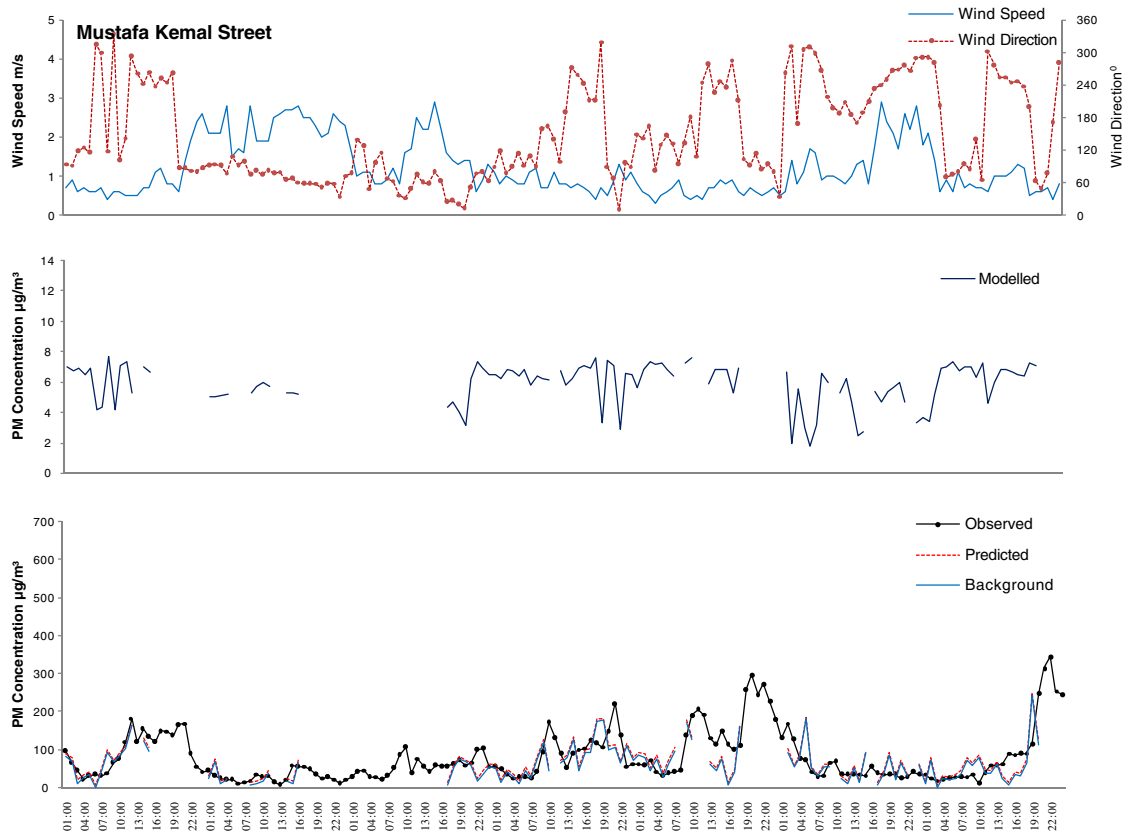
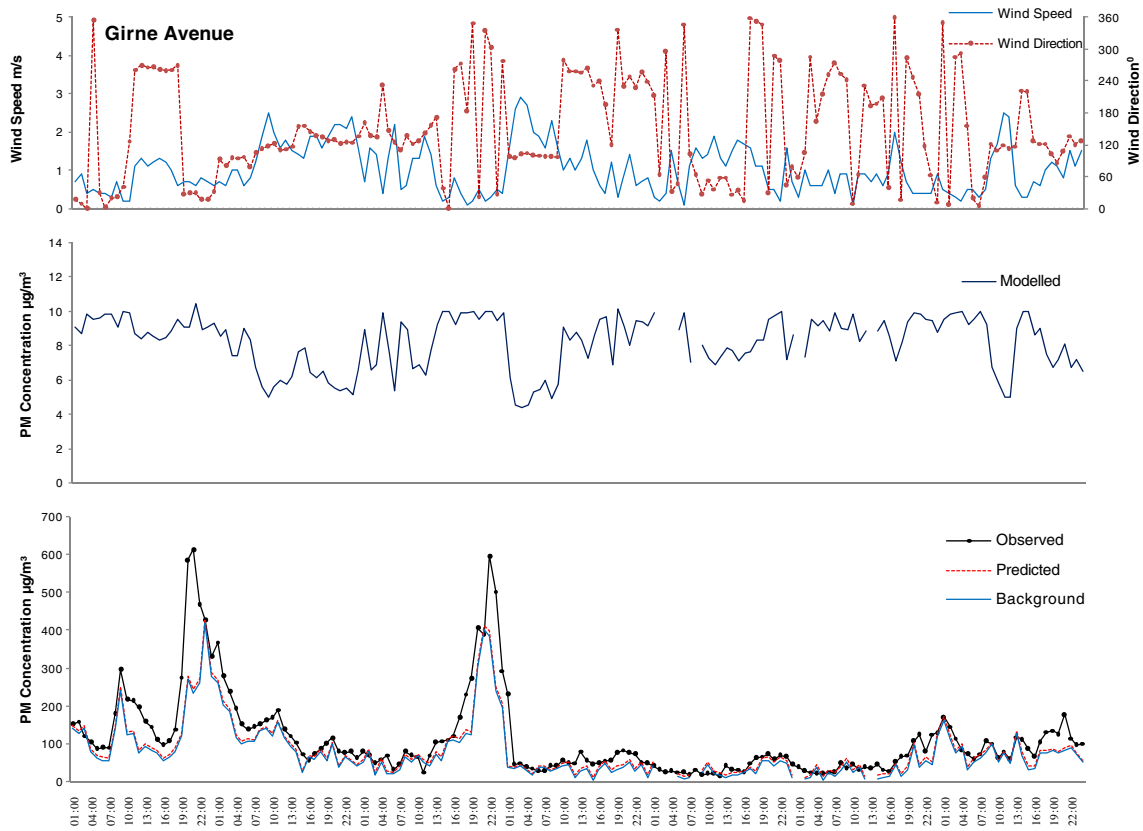
the observed data, and P is the mean value of the predicted data. The correlation coefficient:

$$R = \frac{\sum_{i=1}^N (O_i - O)(P_i - P)}{\sigma_O \sigma_P} \quad (2)$$

where σ_O and σ_P are the standard deviations of observations and predictions. The FB:

$$FB = \frac{(P - O)}{0.5(P + O)}. \quad (3)$$

Fig. 2 Observed, predicted, modeled, and background PM_{10} concentrations in the street canyons (in micrograms per cubic meter). The modeled concentration refers to the contribution from the traffic in the street canyon by removing the background concentration from other sources. The predicted concentration refers to the total concentration by adding the measured average urban background concentrations to the values computed by the OSPM



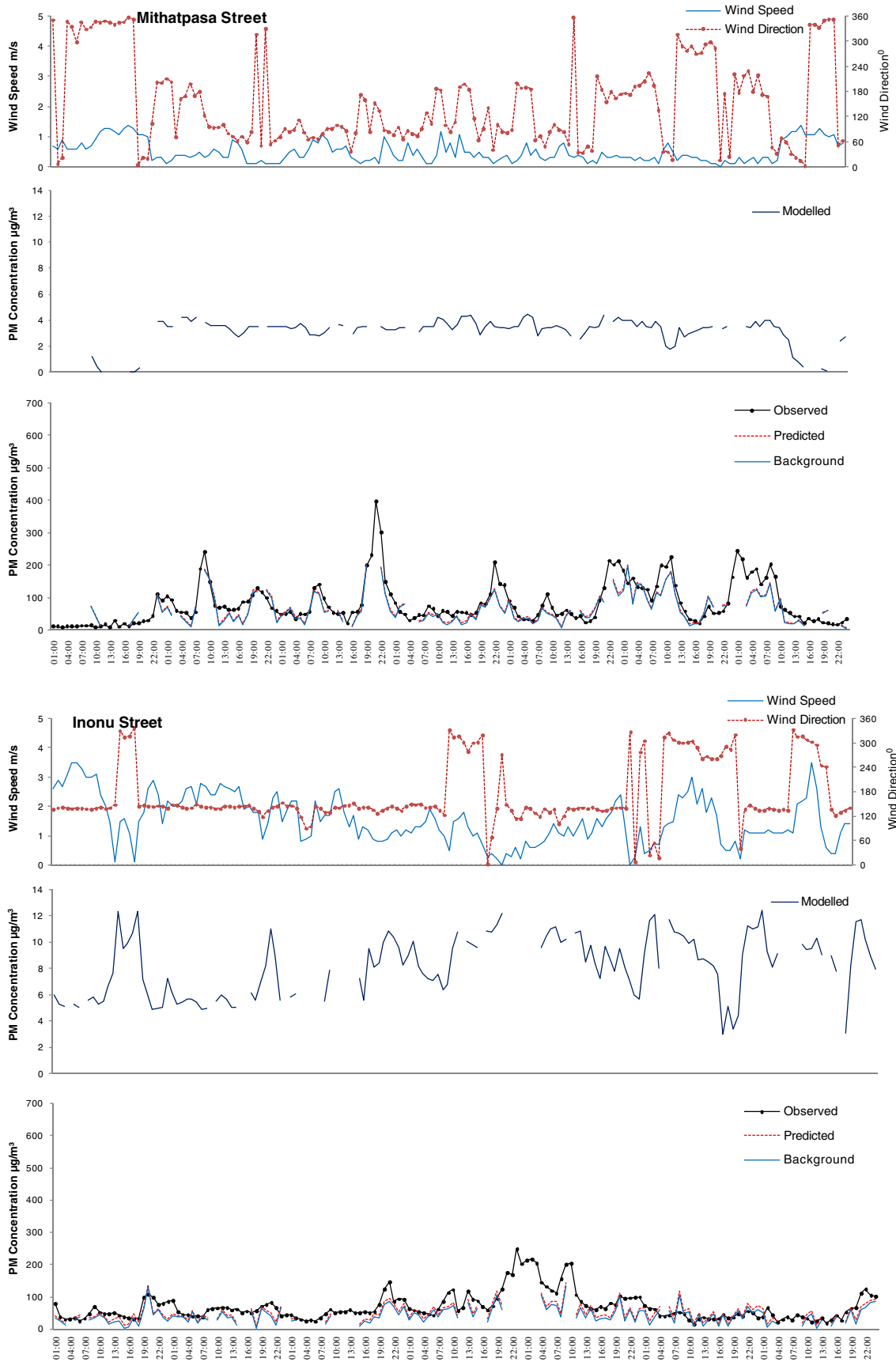


Fig. 2 (continued)

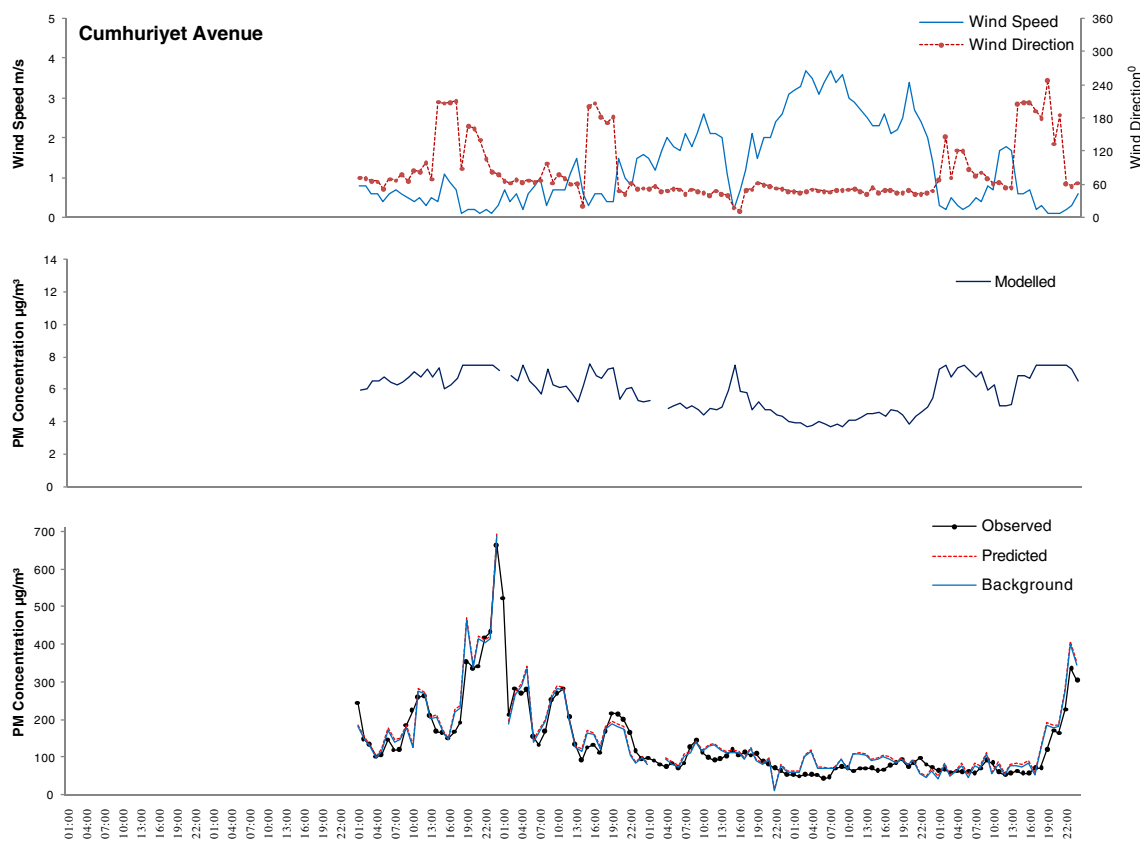


Fig. 2 (continued)

The differences of observed and predicted values are generally caused by the uncertainties in exhaust emission estimates, dispersion modeling, and measurement of concentrations and meteorological data. The stochastic nature of atmospheric turbulence can be also a part of these differences.

Results

The OSPM was tested in five urban street canyons. The hourly time series of street level emissions, urban background concentrations, and meteorological data were used as the input values for OSPM, and OSPM predicted the hourly street level concentrations at the measurement

locations. The agreement between observed and predicted PM₁₀ concentrations in five street canyons was generally good during the measurement campaigns. In Fig. 2, the variations of wind speed and observed and predicted concentrations are plotted for five street canyons. The predicted concentrations show similar trends with the observed concentrations at the same height in the street canyons, including the peak values at the morning and evening hours. Figure 2 indicates that hourly variations are relatively well predicted by OSPM and the wind speed affects the concentration variations. The concentrations tend to be smaller for the higher wind speed cases ($u > 1.5$ m/s), and almost all of the highest concentrations occur for the low wind speed cases ($u \leq 1.5$ m/s).

Table 2 Traffic volume and vehicle category pattern in the street canyons

Street name	Total traffic (vehicles per week)	Motorcycle (%)	Passenger cars (%)	Vans (%)	Trucks and busses (%)
Mustafa Kemal Street	104,643	1.4	71.1	23.5	4.1
Cumhuriyet Avenue	345,662	1.3	92.4	3.7	2.7
Girne Avenue	234,577	2.6	82.0	10.5	4.9
Mithatpasa Street	213,133	2.3	81.6	12.2	3.9
Inonu Street	290,565	2.0	76.1	16.8	5.2

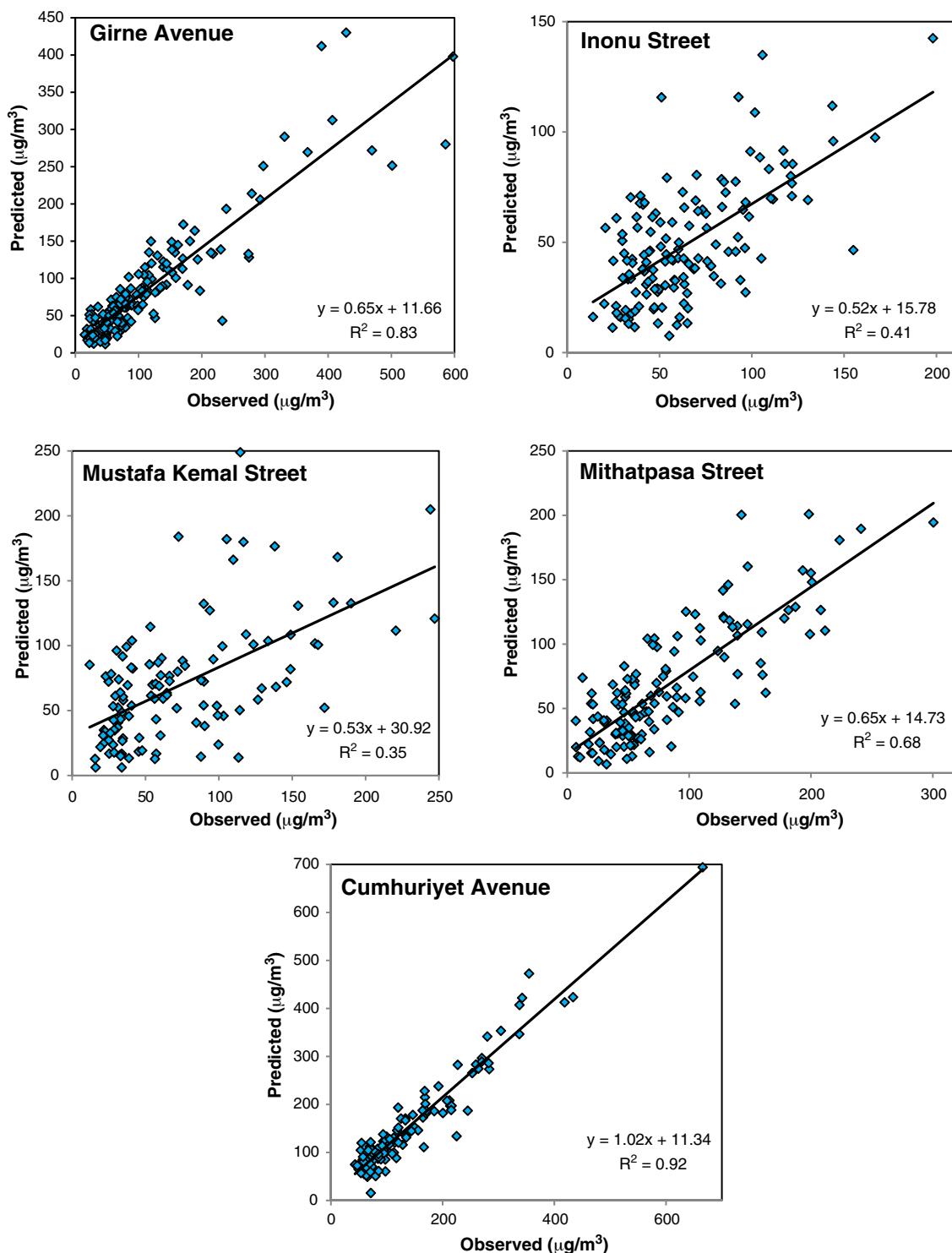


Fig. 3 Scatter plots for comparison of observed and predicted concentrations of PM_{10} (in micrograms per cubic meter)

The traffic counts showed that the traffic densities on the streets were substantial, on average approximately 33,000 vehicles per day. The average proportions of vehicle types in the streets were found to be 2% for motorcycles, 81% for passenger cars, 13% for vans, and 4% for trucks and

buses. The average speeds were observed as 48, 54, 53, and 49 km/h for motorcycles, passenger cars, vans, and trucks and buses, respectively. Traffic volumes and detailed vehicular compositions in the street canyons are presented in Table 2.

The high urban background concentrations observed in the city had a dominant role in the pattern of predicted concentrations in all streets. During the measurement campaigns, the domestic heating sources due to burning of lignite that is the main fuel in the winter period in the city were the main reason for high background PM₁₀ concentrations (Elbir 2002).

The R² values of observed and predicted hourly PM₁₀ concentrations at five street canyons are presented in the scatter plots in Fig. 3. The R² values are 0.92, 0.83, 0.68, 0.41, and 0.35 (*p*<0.01), while the slope values are 1.02, 0.65, 0.65, 0.52, and 0.53 for Cumhuriyet, Girne, Mithatpasa, Inonu, and Mustafa Kemal streets, respectively. The values of IA for the streets are 0.98, 0.91, 0.87, 0.74, and 0.76, respectively. The FB values also range from −0.28 to 0.09. Table 3 summarizes the statistical evaluation results for the hourly data. These statistical values indicated a very good agreement between the temporal variations of predicted and observed concentrations for the symmetric canyons (Cumhuriyet Avenue, a fairly good agreement for Girne Avenue and Mithatpasa Street). The OSPM performs slightly better for leeward side in the symmetric canyons (Cumhuriyet Avenue and Girne Avenue) than windward side in a symmetric canyon (Mithatpasa Street). The main reason is that the leeward side is influenced directly by the traffic emissions in the street in addition to the recirculated polluted air and urban background air, whereas the windward sector is only influenced by the urban background air and the recirculated contribution from street level emissions.

The agreement between the measured and predicted concentrations for asymmetric canyons (Inonu and Mustafa Kemal streets) was lower. The asymmetric canyons mean that buildings flanking these streets have not the same heights along the both sides of the streets. There are some open areas along these streets. These openings may cause that the background concentrations do not represent the background; they rather are affected by the adjacent streets. These open areas along the Inonu and Mustafa Kemal street canyons may cause a relatively higher dilution for PM emissions. Flow characteristics in these streets are probably not fully developed and representative of a typical street canyon because of flow disturbances caused by the openings. The appreciably lower concentrations measured in Inonu and Mustafa Kemal streets (Fig. 3) supports the hypothesis that the openings along these streets may be an important factor for higher dilution of PM emissions, also causing the relatively lower agreement between the measured and modeled concentrations.

The statistical indicators calculated in this study show that the results of application of OSPM are in a good agreement with the previously published studies by Kukkonen et al. (2001) (R²=0.66–0.83, Bias=−0.042 to

Table 3 The statistical analyses of observed and predicted hourly time series of PM₁₀ concentrations in the street canyons

	Girne Avenue			Cumhuriyet Avenue			Inonu Street			Mustafa Kemal Street			Mithatpasa Street		
	Observed	Predicted	Background	Observed	Predicted	Background	Observed	Predicted	Background	Observed	Predicted	Background	Observed	Predicted	Background
Mean (µg m ⁻³)	111.9	84.4	77.1	138.7	152.6	146.7	64.6	49.1	41.5	72.0	68.7	62.8	81.9	67.8	64.7
Maximum (µg m ⁻³)	597.5	430.1	421	665.6	694.2	687	198.1	142.5	132	247.1	249.0	242	300.5	201.0	198
Standard deviation (µg m ⁻³)	104.4	74.3	74.8	98.6	104.5	103.9	32.7	26.5	26.8	51.7	46.2	46.0	57.0	44.8	44.5
Number of valid observation (N)	162			117			139			116			134		
IA	0.91			0.98			0.74			0.76			0.87		
Correlation coefficient (R ²)	0.83			0.92			0.41			0.35			0.68		
FB	−0.28			0.09			−0.27			−0.05			−0.19		

0.22), Kukkonen et al. (2003) (IA=0.81–0.89, $R^2=0.49$ –0.66), Gokhale et al. (2005) (IA=0.77–0.92, $R=0.51$ –0.83), Vardoulakis et al. (2007) ($R=0.82$, Bias=–0.08), and Assael et al. (2008) (IA=0.65, Bias=–0.36). The best agreement between predicted and observed PM₁₀ concentrations (IA=0.98, $R^2=0.92$) was found for Cumhuriyet Avenue in this study. These values are found as the best agreement in overall studies in literature. Cumhuriyet Avenue is a street with a very intensive traffic (about 345,700 vehicles per week) and is in a prolongation of several major streets.

Conclusion

The OSPM was applied to five street canyons in the city of Izmir, Turkey. The results were compared with observations from a mobile air quality monitoring station in the same streets. The results of applications of OSPM to five street canyons indicated that the model could be used as a predictive tool for the determination of air pollution from traffic in the streets. Statistical indicators such as IA and coefficient of determination for all the streets studied were in good agreement with measurements.

Urban background PM₁₀ concentrations were highest during the measurement campaigns in the street canyons. This clearly means that, although part of the accumulated traffic pollution is included in the background, most of the problem arises from the domestic heating activities in the city. This causes that the street canyon PM₁₀ contributions were much lower than the contributions from the surrounding urban background concentrations. The relative contribution of the background concentration compared to the measured values change between 64% and 87% for the five streets.

The model's sensitivity to the street geometry revealed that the model performance is not good when it is applied to asymmetric street canyons. OSPM is also found as a highly simplified and parameterized model representing the detailed dispersion conditions in street canyons and it can be successfully applied for the prediction of pollution from street traffic.

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