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Air pollution forecasting in Ankara, Turkey using air pollution index and its relation to assimilative capacity of the atmosphere

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Abstract Spatial and temporal variations in concentrations of CO, NO, NO_2, SO_2, and PM_{10}, measured between 1999 and 2000, at traffic-impacted and residential stations in Ankara were investigated. Air quality in residential areas was found to be influenced by traffic activities in the city. Pollutant ratios were proven to be reliable tracers to differentiate between different sources. Air pollution index (API) of the whole city was calculated to evaluate the level of air quality in Ankara. Multiple linear regression model was developed for forecasting API in Ankara. The correlation coefficients were found to be 0.79 and 0.63 for different time periods. The assimilative capacity of Ankara atmosphere was calculated in terms of ventilation coefficient (VC). The relation between API and VC was investigated and found that the air quality in Ankara was determined by meteorology rather than emissions.

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Introduction

Urban air pollution is an old and common problem. It changed form, but never disappeared completely. Degradation of urban air quality attracted attention because of its adverse effects on human health (Makri and Stilianakis 2008; O'Connor et al. 2008; Bernstein et al. 2008; Kampa and Castanas 2008; Brunekreef 2007), its impact on material (Lorenzo et al. 2007; Vallet et al. 2006) and on visibility (Rokjin et al. 2006; Young et al. 2006; Hand et al. 2002). Pollutant emissions, particularly from combustion for space heating and transportation (Braniš et al. 2009; Tsikardani et al. 2006; Bellander et al. 2001; Rosenlund et al. 2008; Costabile and Allegrini 2008; Yuval et al. 2008; Fenger 1999), local meteorology (Fisher et al. 2001, 2006; Aldrin and Haff 2005), and topography (Sládek et al. 2007; Kadja et al. 1998), are the main contributors to urban air pollution episodes.

Use of natural gas for space heating resulted in a significant improvement of air quality in most of the Turkish cities in the last 20 years. However, high SO_2 and particulate matter (PM) levels continued to be a concern in large metropolitan areas where coal combustion is still an important mode of residential heating in low-income districts (Tayanç and Berçin 2007; Akay and Yıldız 2007; Taşdemir et al. 2005; Turalıoglu 2005) and around industrial areas (Nuhoglu 2005; Mendil et al. 2005; Yenisoy and Tuncel 2004). Contribution of motor vehicles on urban air quality was also well documented for various cities in Turkey (Taşdemir and Esen 2008; Karaca et al. 2008; Yay et al. 2008; Yatkin and Bayram 2008; Soylu 2007; Koc et al. 2004).

Studies cited above and others demonstrated that unlike strongly regulated cities in Europe and North America where traffic have dominating influence on observed levels of air pollutants, urban airshed in Turkey is under the influence of mixed traffic and heating emissions. Relative contributions of traffic and space heating on observed pollutant levels change from one city to another depending on the population, wealth of the city, and duration and strength of the winter season (Yatın et al. 2000).

In this study, air quality data measured at seven residential and three curbside monitoring stations in the city of Ankara, between 1999 and 2000, were discussed. The primary goal of this study was to provide information on the contribution of traffic emissions on residential sites and to evaluate relative contributions of emissions and meteorology on measured pollutant concentrations. The air pollution index (API) for the city was calculated and used, along with meteorological parameters, to forecast the next day's API. Calculated API was also compared with hourly ventilation coefficient, which is an indicator of the dispersion potential of the atmosphere.

Materials and methods

Ankara is the national capital with 3.5 million inhabitants. It is situated on the Anatolian Plateau (39°55′05″ N, 32°51′04″ E) and surrounded by hills at the north, east, and south. The average height at this part of the Plateau is 900 m above sea level. Ankara, like most of the large urban centers in Turkey, suffered rapid urbanization in the last 30 years. Population increased by 25% between the years 1990 and 2000 due to migration from countryside. Ankara is not an industrial city. Residential heating and motor vehicle emissions are the major sources of air pollution (Yatın et al. 2000). The number of motor vehicles in Ankara increased sharply from 370,000 in 1990 to 850,000 in 2003 as a result of population increase (MATRA Project 2004). Approximately 20% of these vehicles are diesel-powered.

Measurements were carried out at seven residential and three traffic stations. Traffic stations were located at three very crowded street junctions, namely, Iskitler, Kizilay, and Kavaklidere. Air quality parameters measured in these three stations included CO, NO, NO_2, SO_2, and PM_{10}. The seven residential stations included in this study were the stations of the Ankara Air Quality Monitoring Network, which was operated by the Ministry of Health, Refik Saydam Hygiene Center. These stations were located at residential areas in different districts of the city. These stations were not under direct influence of motor vehicle emissions. Only SO_2 and PM_{10} were measured in six of the residential stations (K.esat, Besevler, D.evler, Keçiören, Çankaya, and Yenidogan). Besides SO_2 and PM_{10}, concentrations of NO and NO_2 were also measured in the seventh residential station (Sihhiye). Measurements in all stations were continuous and integration time was 60 min. Locations of traffic and residential stations are depicted in Fig. 1.

Curbside stations were operated between October 1999 and August 2000. Although data from residential stations were continuous (the monitoring network has been in operation since 1985), data from the period between October 1999 and August 2000 were used in this study.

Automated analyzers were employed in all stations. Carbon monoxide was measured by infrared gas filter correlation (Environment S.A, model 48C), NO and NO_2 by chemiluminescence (Environment S.A., model AC 31M), SO_2 by UV fluorescence (Environment S.A., model AF 22M), and PM_{10} by β-ray attenuation (Environment S.A., model MP101M). Gas analyzers were calibrated using certified calibration gases and calibrations were checked daily using permeation tubes. Beta gauge, on the other hand, was calibrated using a certified foil supplied by the manufacturer.

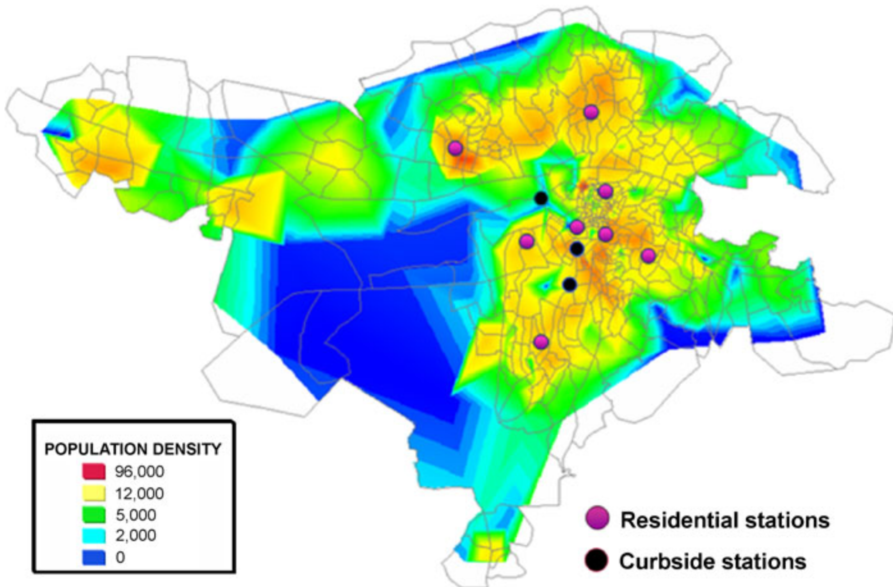


Fig. 1 Map showing the locations of the monitoring stations and distribution of population in Ankara

Results and discussion

Current state of pollution

Long-term standards in Turkish air quality regulation (TAQR; values which should be compared with 1-year average values in monitoring results) are 150 μg m^{-3} for SO_2 and PM_{10} and 100 μg m^{-3} for NO_2 (MOE 1986). Average concentrations of pollutants measured in both residential and curbside stations complied with TAQR standards. However, average values are not in compliance with the European Union (EU) directives, where long-term (1-year) standards are 40 μg m^{-3} for PM_{10} and NO_2 and 20 μg m^{-3} for SO_2, or with the World Health Organization guideline values (50, 20, and 40 μg m^{-3} for SO_2, PM_{10}, and NO_2, respectively). New actions to improve air quality in Ankara will be necessary in the near future because TAQR is now being revised to make it compatible with corresponding EU directives.

Spatial distribution of SO_2 and PM_{10} concentrations

Concentrations of parameters measured at traffic and residential stations are given in Table 1. Median values of parameters are more representative for data population, as chi-square test demonstrated that measured parameters are log-normally distributed in all stations with 95% statistical confidence. Average concentrations are also included in the table to facilitate comparison with literature values where arithmetic mean values of pollutant concentrations are generally reported.

Concentrations of SO_2 varied between 63 and 110 μg m^{-3} and 32 and 79 μg m^{-3} at curbside and residential stations, respectively. Concentrations of PM_{10}, on the other hand, varied between 50 and 74 μg m^{-3} at traffic stations and between 40 and 85 μg m^{-3} at residential stations. Mann–Whitney test were used to test statistical significance of differences observed between median SO_2 and PM_{10} concentrations measured at traffic-impacted and residential stations. Results demonstrated that differences between median SO_2 and PM_{10} concentrations measured at traffic and residential stations were statistically significant with 95% confidence. Median concentrations of pollutants measured at three traffic-impacted stations were also different, within 95% confidence interval, which signified the influence of different traffic intensity on pollutant concentrations measured in these stations. However, Mann–Whitney test also demonstrated that median SO_2 and PM_{10} concentrations measured at residential stations are not different from each other with 95% statistical

Table 1 Average and median concentrations of measured parameters at traffic and residential stations

		Number	Average ($\mu g\ m^{-3}$)	Median ($\mu g\ m^{-3}$)
Iskitler	CO	1,771	8,400 ± 6,600	6,900
	NO	1,589	290 ± 250	220
	NO_2	1,590	79 ± 99	46
	SO_2	1,729	130 ± 91	110
	PM_{10}	1,691	96 ± 76	74
Kavaklidere	CO	1,095	7,100 ± 5,100	5,800
	NO	1,028	160 ± 130	130
	NO_2	1,028	41 ± 32	35
	SO_2	1,056	77 ± 59	63
	PM_{10}	999	62 ± 42	50
Kizilay	CO	1,044	6,500 ± 3,900	5,700
	NO	957	250 ± 240	170
	NO_2	957	110 ± 110	51
	SO_2	805	130 ± 90	110
	PM_{10}	720	80 ± 67	60
Sihhiye	CO	7,248	3,700 ± 3,100	3,100
	NO	7,513	100 ± 120	64
	NO_2	7,548	110 ± 64	100
	SO_2	2,369	70 ± 47	60
	PM_{10}	2,397	88 ± 71	70
K.esat	SO_2	2,388	61 ± 46	47
	PM_{10}	2,261	100 ± 79	85
Çankaya	SO_2	2,412	46 ± 39	32
	PM_{10}	2,401	52 ± 42	40
Besevler	SO_2	2,249	100 ± 83	79
	PM_{10}	2,184	110 ± 100	80
D.evler	SO_2	1,146	59 ± 50	44
	PM_{10}	1,642	120 ± 110	85
Keçiören	SO_2	2,260	77 ± 78	55
	PM_{10}	2,350	94 ± 96	60
Yenidogan	SO_2	2,338	65 ± 65	41
	PM_{10}	2,271	100 ± 110	69

confidence. Spatial uniformity in SO_2 and PM_{10} concentrations can be an indication of a well-mixed atmosphere.

A better indicator of the mixing of the atmosphere over Ankara is the correlations between data generated at different stations. The scatter plot matrix, which shows the correlation of SO_2 and PM_{10} concentrations between residential stations, is given in Fig. 2. The r^2 values vary between 0.30 and 0.70 for SO_2 and between 0.22 and 0.74 for PM_{10}. Probability of chance correlations is less than 5% $[P(r, n) < 0.05]$ for all pairs shown in the figure. Both the fairly uniform concentrations of SO_2 and PM_{10} measured in different stations and the presence of statistically significant binary correlations between stations indicate fairly uniform distribution of pollutants, owing to a common factor or factors affecting all residential stations. Similar uniform distribution of pollutants and presence of strong correlations between different measurement stations in Hong Kong were attributed to the long-range transport of pollutants (Hagler et al. 2007). Yatın et al. (2000) explained similar concentrations of trace elements measured at two widely separated sampling locations in Ankara by low wind speed. The uniformity of concentrations and correlations which was between stations observed in this study is probably due to local meteorology rather than long-range transport. There are no strong sources or source regions around Ankara, which can affect pollutant concentrations in the whole city. The average annual wind speed (WS) in Ankara is only 2.0 m s^{-1}, which indicates that calm conditions (WS < 1.0 m s^{-1}) are frequent and strong winds are rare in Ankara. Such slow winds result in uniform distribution of pollutant concentrations and observed correlations between stations. The relation between pollutant concentrations and meteorology will be further discussed in this article.

Temporal variations in pollutant concentrations

Monthly average SO_2, PM_{10}, CO, and NO concentrations measured at residential and traffic stations are given in Fig. 3. The division of the year as summer and winter is based on the operation of residential heating units. In Ankara, as a rule set by the Municipality, residential heating units are not allowed to operate before October, and they are not allowed to operate when the daily average temperature exceeds 15°C, which occurs around April 15. Based on these, summer and winter seasons in this study were between April–September and October–March, respectively. Concentrations of all measured parameters demonstrated well-defined seasonal variations, with higher concentrations during winter months.

Winter-to-summer concentration ratios varied between 1.3 and 2.3 for CO and NO, which were primary pollutants emitted from vehicle exhaust. Seasonal variations in both meteorology and vehicle emissions favored high concentrations of these parameters during winter season. Seasonal

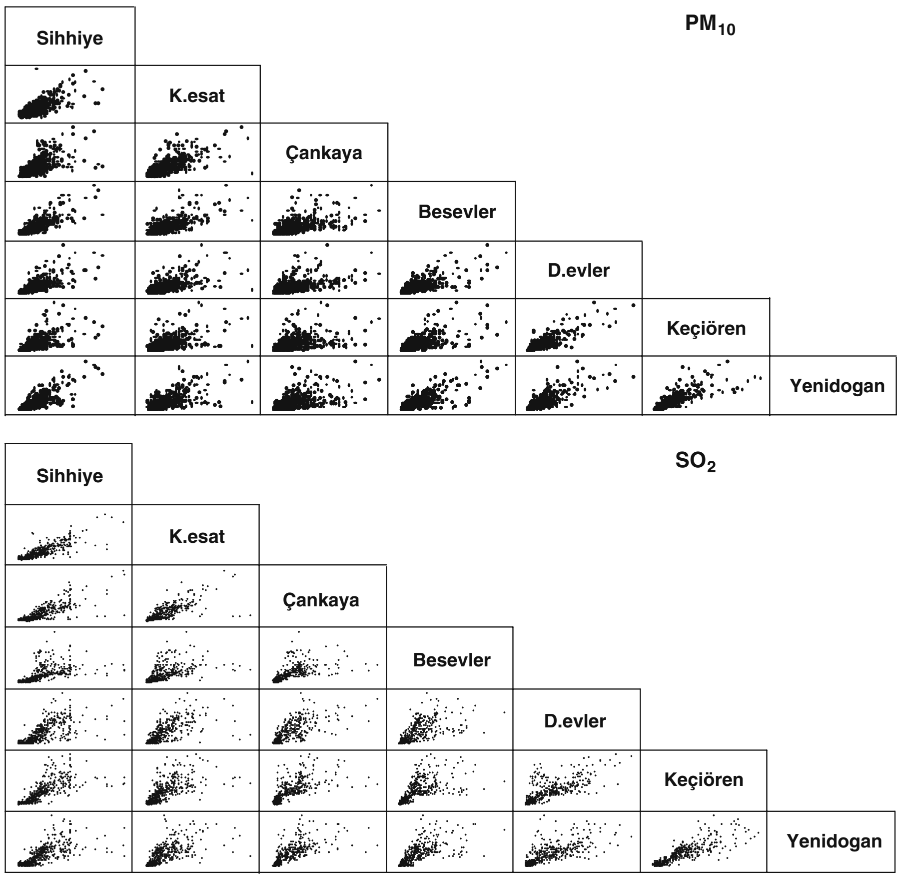


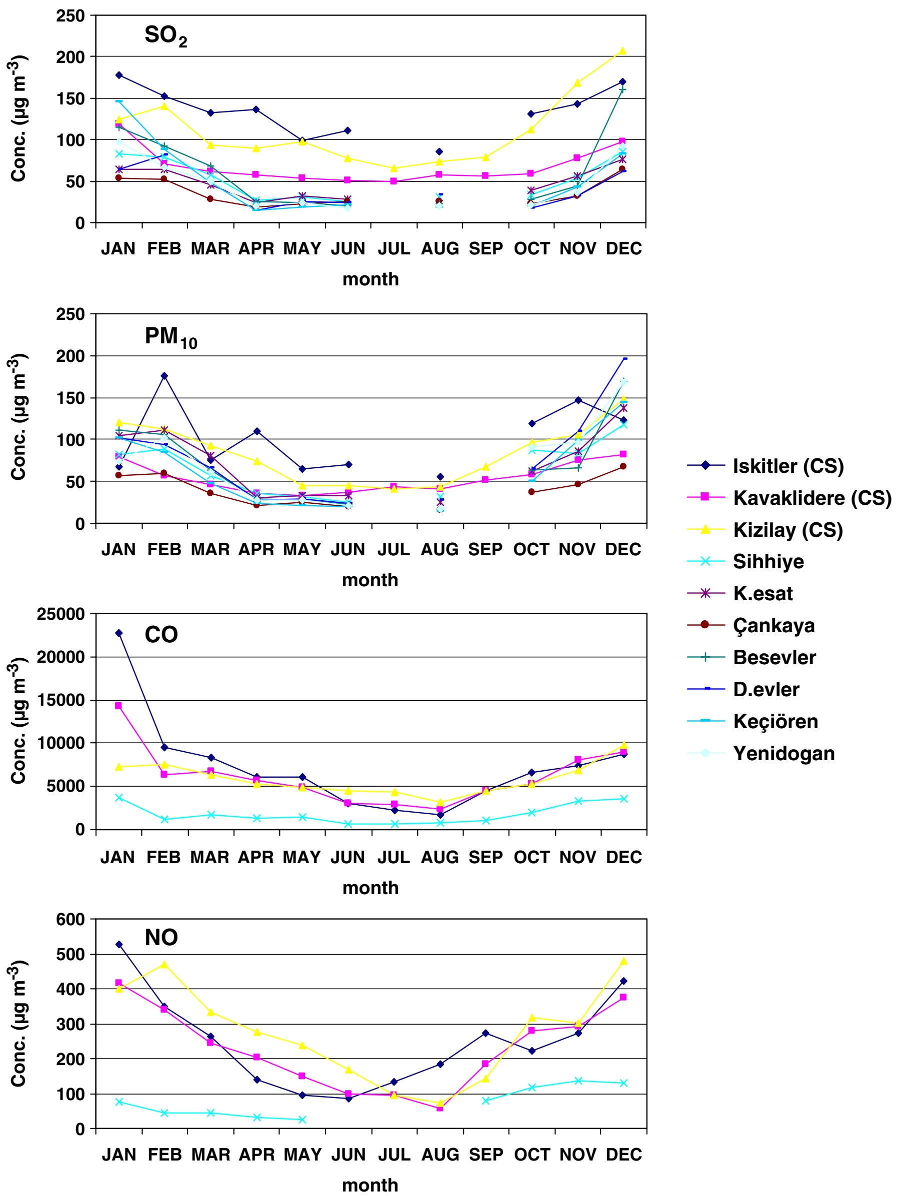
Fig. 2 Correlation of SO_2 and PM_{10} concentrations between residential stations

changes in meteorology favored high concentrations not only of traffic-related pollutants but of all pollutants during winter season because the mixing height in Ankara was approximately 50% deeper during the summer season (Yatın et al. 2000). Variations in emissions also favored high concentrations of traffic-related pollutants during winter because the number of vehicles in traffic is approximately 25–30% smaller during the summer months (Ankara Municipality, unpublished data).

Concentrations of SO_2 and PM_{10} were also higher during winter at both residential and curbside stations. However, winter-to-summer SO_2 concentration ratios were different between traffic and residential stations, with a 95% statistical significance. The ratio of SO_2 concentrations measured in winter to those measured in summer varied between 1.6 and 3.9 at residential stations and between 1.0 and 1.8 at the three curbside stations. Observed difference was probably due to different contributions of space heating and traffic sources on these two station groups. At curbside stations, diesel emissions were the main SO_2 source, which did not change significantly between summer and winter seasons. Higher winter SO_2 concentrations measured at curbside stations were due to better ventilation conditions that prevailed during the summer months.

A substantial effort was spent to convert heating units to natural gas; however, 67% of the residences in Ankara are still being heated by burning coal (Ankara Municipality, unpublished data). The coal burning generally occurs in the low-income districts where the infrastructure is not adequate for the conversion of heating systems to natural gas. Most of these districts are located at the outskirts of the city, particularly to the north and south of Ankara. The main SO_2 source at residential stations was coal combustion, which

Fig. 3 Monthly average concentrations of measured parameters at curbside and residential stations



was intense during winter but completely disappeared during summer. This generated a large difference between winter and summer SO_2 concentrations. Unlike SO_2, winter-to-summer PM_{10} concentration ratio was not significantly different at traffic and residential stations. In both station groups, winter-to-summer ratios were approximately 2. Similarities between winter-to-summer PM_{10} ratios at curbside and residential stations were due to replacement of combustion sources with natural PM_{10} sources in summer. Large decrease in combustion particles during summer was probably replaced by enhanced soil resuspension.

Diurnal variation in concentrations of traffic-related pollutants, CO, NO, and NO_2, at the curbside stations and at the Sihhiye station are given in Fig. 4a–c. Concentrations of CO and NO, at all stations, showed well-defined diurnal variation with two rush hour maxima, which is typical for motor-vehicle-related pollutants. Carbon

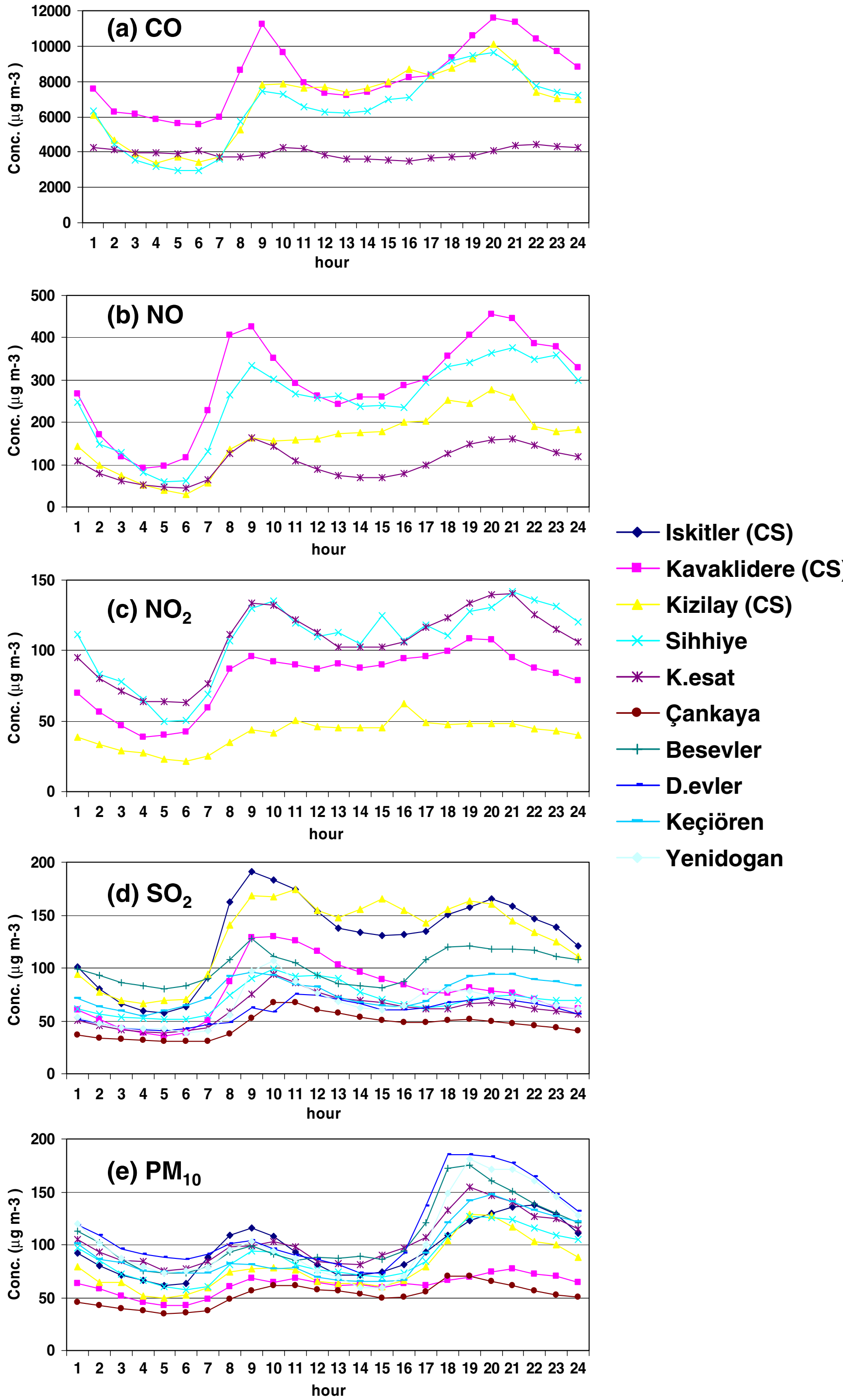


Fig. 4 Diurnal variation of measured parameters

monoxide and NO concentrations measured at the Sihhiye station were lower than the concentrations measured at the curbside stations, particularly during rush hours. The difference was due to closer proximity of curbside stations to traffic emissions.

However, NO_2 concentrations measured at Sihhiye station were not only higher than NO_2 concentrations measured at the curbside stations but also depicted a better defined traffic pattern, with two rush hour maxima, than those observed at curbside stations. Concentration of NO_2 was low and diurnal pattern was poorly defined at curbside stations because the Δt, the interval between the time at which NO was emitted from exhaust and the time it reached the inlet of the measurement system, was too short for extensive formation of NO_2.

Diurnal variations in SO_2 and PM_{10} concentrations are given in Fig. 4d, e. Diurnal variations observed at residential and curbside stations were similar, except for a small time shift at the peak hours at some residential stations. The rush hour patterns observed in the concentrations of SO_2 and PM_{10} indicate that traffic emissions contributed to SO_2 and PM_{10} concentrations measured at the residential stations. This conclusion was in agreement with the findings of Yatın et al. (2000) where authors reported that contribution of motor vehicles to PM_{10} mass was 40% at the sampling point that was far from major roads in Ankara.

Pollutant ratios

Parameters measured in this study are not powerful tracers for source identification because they are emitted from both motor vehicles and combustion sources. However, ratios of pollutant concentrations, particularly PM_{10}-to-SO_2 and NO-to-NO_2 ratios, proved to be more informative than the pollutants themselves to differentiate between different sources.

Summer and winter median concentrations for PM_{10}-to-SO_2 and NO-to-NO_2 ratios are given in Table 2. The PM_{10}-to-SO_2 ratio varied between 0.51–0.88 and 0.84–2.18 at curbside and residential stations, respectively. The difference between two station groups was statistically significant at 95% confidence level. Since resuspended soil component in PM_{10} mass was at the minimum level during winter, the difference between ratios calculated for curbside and residential stations during winter season probably resulted from the difference between PM_{10}-to-SO_2 ratios in diesel- and combustion-related emissions.

Table 2 PM_{10}/SO_2 and NO/NO_2 ratios measured at curbside and residential stations

	PM_{10}/SO_2		NO/NO_2	
	Summer	Winter	Summer	Winter
Kizilay	0.51	0.66	1.88	4.06
Iskitler	0.52	0.88	2.54	5.38
Kavaklidere	0.71	0.79	2.94	4.20
Sihhiye	1.02	1.28	0.30	1.30
K.esat	1.12	1.68		
Çankaya	0.84	1.17		
Besevler	1.00	1.08		
D.evler	0.97	2.18		
Keçiören	0.96	1.24		
Yenidogan	1.07	1.58		

A well-defined diurnal pattern, with higher PM_{10}-to-SO_2 ratios during nighttime, was observed both at curbside and residential stations, as depicted in Fig. 5a. The pattern was more evident at residential stations. Observed diurnal variation in PM_{10}-to-SO_2 ratio was due to higher contribution of motor vehicle, which had smaller PM_{10}-to-SO_2 ratio, during the day. At night, observed PM_{10}-to-SO_2 ratios were higher due to increased space heating emissions and reduced traffic activity.

Median values of NO-to-NO_2 concentration ratio at curbside stations varied between 4.06 and 5.38 in winter and 1.88 and 2.94 in summer. Higher ratios, which were observed in winter, were due to reduced photochemical activity. The NO-to-NO_2 ratio measured at Sihhiye station (the only residential station where NO and NO_2 were measured) was 1.30 in winter and 0.30 in summer. Both of these values were lower than corresponding ratios calculated for curbside stations. This can be attributed to longer distance (and thus transport time) between emission and measurement points, allowing for more extensive conversion of NO to NO_2. The diurnal pattern in NO-to-NO_2 ratio, which is given in Fig. 5b, is similar to the traffic pattern observed in those stations.

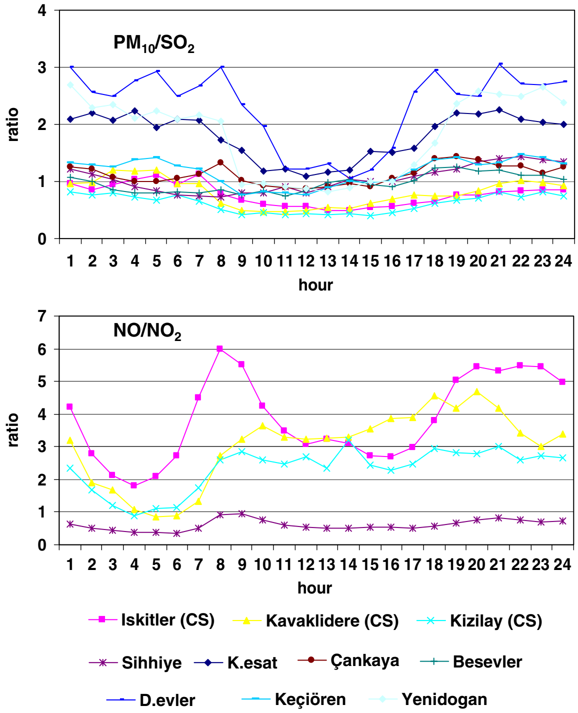


Fig. 5 Diurnal variation of PM_{10}-to-SO_2 ratios and NO-to-NO_2 ratios

Relation with meteorology

The city of Ankara has a typical inland climate with dry and hot summers and cold winters. Daily mean temperature in winter is 2.4°C, but temperatures as low as −20°C are frequent in winter season. Summer average temperature is 22.8°C, but again, temperatures close to 40°C are frequent, particularly during June, July, and August. Annual mean rainfall is approximately 420 mm, which is among the lowest annual average rainfall values in the whole country. The most important feature of the local meteorology in terms of air quality is the very low average wind speed. Annual average wind speed is approximately 2 m s^{-1}, which is at least partly responsible for extremely heavy pollution episodes observed in the past (Yatın et al. 2000).

It is well documented that concentrations of pollutants at an urban airshed are at least partly determined by the meteorological parameters (Fisher et al. 2006; McGibbony et al. 2005; Vignati et al. 1996). The relation between measured pollutant concentrations and wind speed and wind direction and mixing height was investigated to recognize the role of these meteorological parameters on the current air quality in Ankara.

No statistically significant relation (within 0.95 confidence interval) was found between wind speed and pollutant concentrations at curbside stations. However, concentrations of all measured parameters decreased with increasing wind speed at residential stations. The observed relation between the wind speed and concentrations were statistically significant at 95% confidence level when the wind speed was $\geq$3.0 m s^{-1}. The relation was not statistically significant at slower winds.

Another parameter with which pollutant concentrations measured at residential stations were related was the mixing height. In this study, hourly mixing height was calculated using PCRAMMET software, which is a meteorological processor commonly used in dispersion modeling (Kim et al. 2003). Radiosonde data from Ankara Meteorological Station were used in calculations. Mixing height showed a strong diurnal pattern in summer, varying between 2,200 m at approximately 1500 hours and 500 m during the night. In winter, however, it varied around 500 m, with slightly higher values during daytime, without a strong diurnal pattern. Concentrations of pollutants observed at curbside stations did not show any statistically significant dependence on mixing height due to very short distance (≈3 m) between emissions and the sampler inlet in these stations. However, concentrations of pollutants measured at residential stations showed a clear, statistically significant (with 95% confidence) decrease with increasing mixing height, as expected.

Pollutants measured at curbside stations did not show a detectable dependence on wind direction as well. Since curbside stations were located in the middle of the junctions and motor vehicle emissions originated from all directions, wind direction did not have a strong influence on pollutant concentrations. However, concentrations of pollutants measured at residential stations were dependent on wind direction because pollutant sources were not homogeneously distributed around these stations.

Wind direction itself also showed a strong directionality during the study. North–northeast and

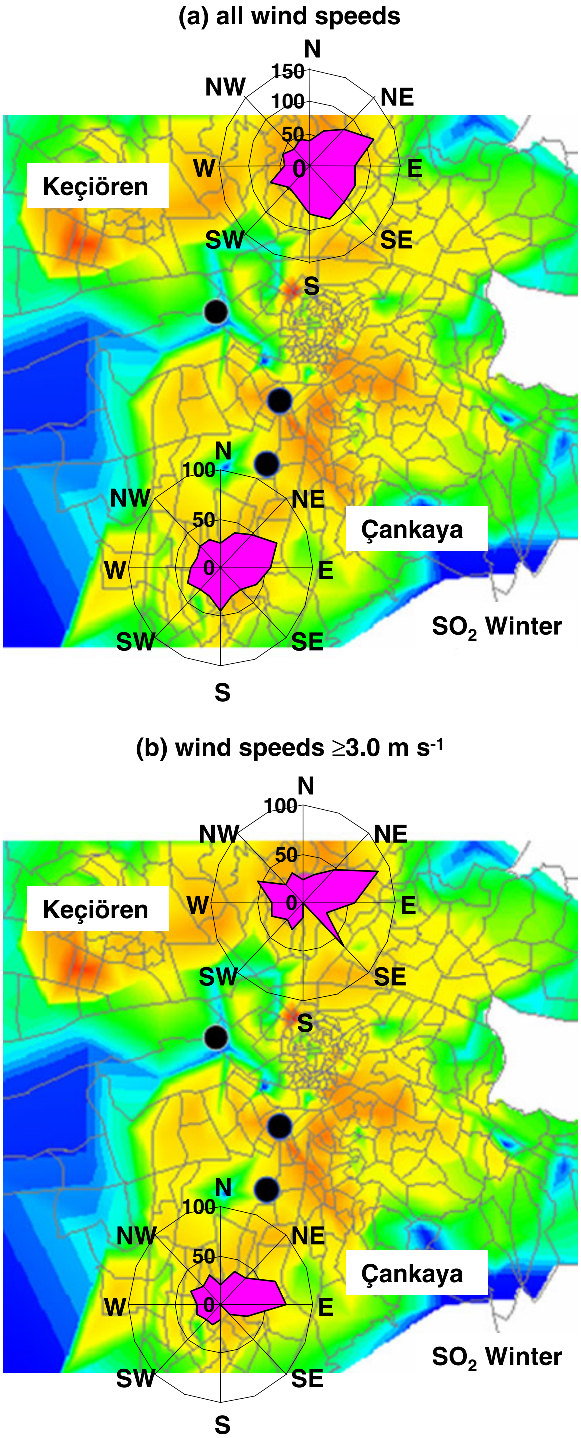


Fig. 6 Dependence of SO_2 concentrations ($\mu g\ m^{-3}$) measured at Çankaya and Keçiören stations on wind direction. **a** Pollution roses calculated including all wind speed data. **b** Pollution roses calculated using wind speeds higher than $3.0\ m\ s^{-1}$

SSW sectors accounted for 60% and 30% of all wind observations, respectively. All remaining sectors accounted for only 10% of hourly wind observations during the study period.

Pollution roses (average concentrations of pollutants at each wind sector) calculated for PM_{10} and SO_2 at Çankaya and Keçiören stations are given in Fig. 6a. At both stations, concentrations of PM_{10} and SO_2 concentrations did not show strong sector dependence at low wind speeds. Yatın et al. (2000) also measured comparable concentrations of anthropogenic aerosol-bound trace elements at suburban and downtown stations at Ankara and attributed this observation to accumulation of pollutants over the city due to frequent slow winds and calms.

Concentrations of SO_2 and PM_{10} at Çankaya and Keçiören stations showed stronger sector dependence at wind speeds $\geq 3.0\ m\ s^{-1}$, which is shown in Fig. 6b for SO_2. At both stations, the sector that corresponded to highest SO_2 concentrations was ENE sector. At Keçiören, ENE sector corresponded to squatter settlement districts along the road to the airport. At Çankaya, the same sector pointed to another squatter settlement district, namely, Mamak. Directional dependence of PM_{10} concentration was very similar to the directional dependence of SO_2 concentration. These observations demonstrated that although a large fraction of settlements in the city is being heated by natural gas combustion, coal burning in low-income districts is still an important source of SO_2 and PM_{10} pollution in the districts where coal is not being used for space heating.

Urban air pollution index

API is an approach to express the state of pollution of each air pollution monitoring station in an urban area with one simple number. It is widely used to express air quality level in urban areas (Longhurst 2005; Murena 2004), to find the relation between air quality and meteorology (Wang and Lu 2006; Chen et al. 2008; Chu et al. 2008), and to predict the index for the next day (Jiang et al. 2004; Lang et al. 2004; Zhou et al. 2004; An et al. 2001). In this study, the API of each residential station was calculated for every day between October 1999 and March 2000 using the threshold values suggested by Elshout et al. (2008), and calculated station APIs were summed to obtain the API of the whole city, namely, urban air pollution index (I). Calculated I was regressed against meteorological parameters to forecast the urban air pollution index for the next day. Sulfur dioxide and PM_{10} data measured in residential stations were included in API calculations because NO, NO_2, and CO were not measured in these stations.

The methodology used by Cogliani (2001) was adopted to calculate urban air pollution index (I) for Ankara. Briefly, the highest hourly concentrations of SO_2 and PM_{10} mass measured in a station during a 24-h period were assigned a value of "good," "acceptable," or "poor" depending on the criteria given in Table 3. Since API needs to be numerical, the ratings of parameters had to be converted to numbers. This was done by assigning values of 1, 3, and 7 to "good," "acceptable," and "poor" ratings, respectively. A score of 0 was also assigned for missing values.

If the sum of the pollutant scores in a station was equal to 2, which corresponded to "good" rating in both SO_2 and PM_{10}, the station was assigned a "station score" of 0 (indicating "good" rating for the station). If the sum was between 4 and 6, which means either SO_2 or PM_{10} had a "good" and the other one had "acceptable" ratings, the station was assigned "station score" of 1 (indicating an "acceptable" rating for the station). If the sum of the pollutant scores was between 8 and 14, which means either SO_2 or PM_{10} had "poor" rating (the other parameter could have "good," "acceptable," or "poor" ratings), the station was assigned the score of 2 (indicating a "poor" rating for the station). If there were no data for either pollutant in a station for that day, that station was assigned the score of 2 (poor). The urban air pollution index (I) for Ankara for that particular day was simply calculated by summing all station scores calculated for that day. Using this procedure, urban air pollution index (I) was calculated for every day between October 1999 and March 2000. Although there are no defined criteria to rate calculated urban API, the following systematic was developed and used to rate calculated city API as "good," "acceptable," and "poor".

If calculated API was smaller than 4, the air quality in the city was rated as "good"; if it was between 4 and 12, the air quality was rated as "acceptable"; and if API was >12, then the air quality was rated as "poor." These criteria were based on calculated average API of stations. The variation of API between October 1999 and March 2000 is depicted in Fig. 7. There were 3, 26 and 72 days for which the API was rated as "good," "acceptable," and "poor", respectively, indicating that winter season was dominated by poor air quality in Ankara.

In the second phase of the exercise, calculated daily API values (I) were used to forecast the API value for the next day (I_c). Accuracy of predictions was tested by comparing predicted API values between January and March 2000, with API values calculated from measured air quality data for that period. For forecasting, in the first step, meteorological parameters that showed statistically significant correlation with API were determined. Parameters tested for correlation

Table 3 Hourly threshold values of PM_{10} and SO_2 (Elshout et al. 2008)

Air quality level	Index	PM_{10} ($\mu g\ m^{-3}$)	SO_2 ($\mu g\ m^{-3}$)
Good	Very low	0	0
		25	50
	Low	25	50
		50	100
Acceptable	Medium	50	100
		75	300
Poor	High	75	300
		100	500
	Very high	>100	>500

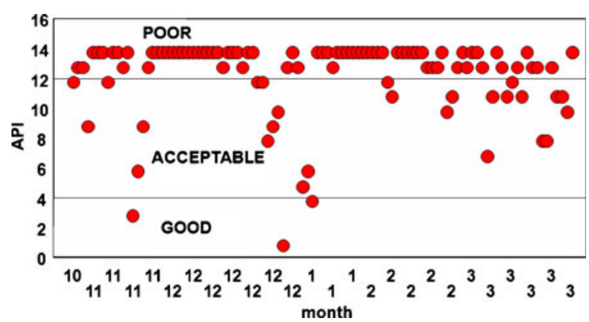


Fig. 7 API of Ankara between October 1999 and March 2000

include daily highest temperature, daily lowest temperature, daily average temperature, daily thermic excursion (difference between the hourly highest temperature and hourly lowest temperature data), daily highest wind speed, daily average wind speed, daily highest mixing height, daily average mixing height, and daily average barometric pressure. Daily average wind speed, daily average barometric pressure, and daily thermic excursion were the only three parameters that showed statistically significant correlation (within 99% confidence interval) with daily API; therefore, other variables were not included in multiple linear regression analysis (MLR) performed in the next step.

In the second step, calculated daily city API (I) was regressed against four independent variables, including daily average wind speed, daily average barometric pressure, daily thermic excursion, and previous day's air pollution index for the period between October 1999 and December 1999. Traffic counts would be a better independent variable than the previous day's API, but such counts were not available for that period. Air pollution index for the previous day was shown to be a reasonably good replacement for traffic counts (Cogliani 2001). The MLR resulted in the following regression equation:

$$I_c = 0.212\Delta T + 0.043P + 0.162I_{d-1} - 1.705V - 27.945$$

where ΔT is the daily thermic excursion (°C), P is the daily average barometric pressure, I_{d-1} is the API of the previous day, and V is the daily average wind speed (m s^{-1}). Air pollution index for the next day (I_c) was then calculated using forecasted meteorological data and the regression equation. Accuracy of the forecasted API value depends on the (1) accuracy of the forecasted meteorological data and the (2) accuracy of the relation between API and meteorological parameters (or the accuracy of the MLR exercise). Meteorological forecasts are 84% accurate for both wind speed and temperature (Turkish State Meteorological Service, unpublished data). The combined effect of meteorological forecast accuracy and accuracy of the MLR exercise was tested by comparing predicted API with the corresponding calculated value for the periods between October 1999–December 1999 and January–March 2000. The first period was the period used to derive regression equation. The second period was a totally independent test period.

The relation between I_c and I for the period between October 1999 and December 1999 is depicted in Fig. 8a. Calculated (I) and predicted (I_c) API values agreed nicely in this data set. The correlation between I and I_c was 0.79, which indicated a statistically significant correlation at 99% confidence level. Since the same ΔT, P, I_{d-1}, and V values were used both to derive regression coefficients and to calculate I_c values, good agreement between I and I_c was not surprising.

To test the method with a totally independent data set, API values for the next day was forecasted (I_c) using the same regression equation with ΔT, P, I_{d-1}, and V values forecasted between January and March 2000. Daily index values (I) were also calculated using air quality

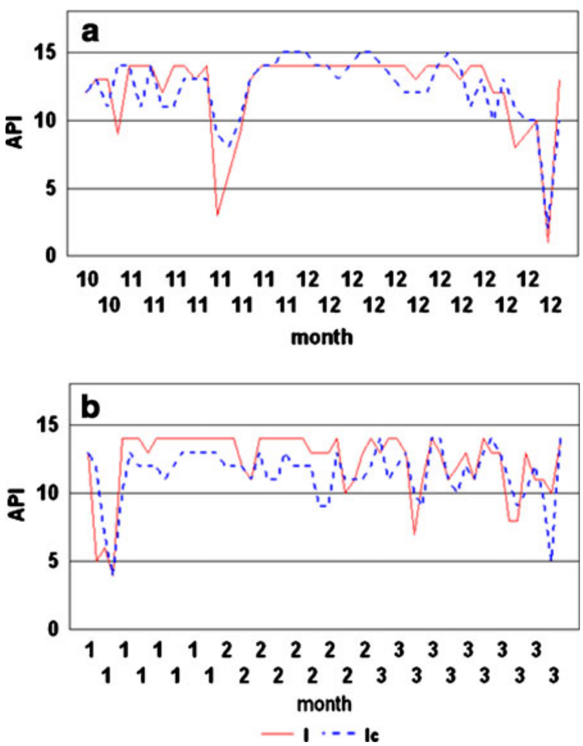


Fig. 8 I and I_c trends versus observation days between October 1999–December 1999 (**a**) and January–March 2000 (**b**)

data generated at residential stations in the same period. The temporal variation of I and I_c in this test period is shown in Fig. 8b. General features in observed API (I) were reasonably closely followed by predicted index values (I_c). Correlation between observed (I) and predicted (I_c) air pollution indices was statistically significant at 99% confidence interval ($[P(0.63, 99)] < 0.01$), which was comparable to agreements reported in other studies (Cogliani 2001; Jiang et al. 2004).

In this study, API was based on SO_2 and PM_{10} as these were the only parameters measured with required frequency and continuity. Measurement of parameters such as CO, NO_2, and O_3 in the monitoring network can improve the index in the future.

Relation between air pollution index and assimilative capacity of the atmosphere

Ventilation coefficient (VC) is the product of surface wind speed and mixing height. Since pollution level in an urban airshed is determined by both horizontal (winds) and vertical (stability) ventilation, VC is expected to provide more reliable information on the contribution of meteorology on air quality than both wind speed and mixing height alone (Goyal and Rao 2007; Goyal et al. 2006; Rama Krishna et al. 2004; Gupta et al. 2003; Manju et al. 2002; Ghose et al. 1999).

In this study, hourly VC was calculated for the years 1999 and 2000. Results were used (1) to evaluate dispersion potential of the atmosphere in summer and winter seasons and (2) to investigate the possible relation between ventilation coefficient and API. In VC calculations, surface wind speed data were obtained from the Ankara Meteorological Station and hourly mixing height was calculated from Ankara radiosonde data using PCRAMMET software (EPA 1999).

Dispersion condition in Ankara atmosphere was considered as poor, fair, good, and excellent when the value of VC was between 0 and 2,000, 2,001 and 4,000, 4,001 and 6,000 and >6,000, respectively. The criteria were adopted from Eagleman (1991).

Annual and seasonal frequency of occurrence of VCs in Ankara is shown in Fig. 9, together with diurnal variations in VC, wind speed, and urban mixing height in the summer and winter seasons. Poor dispersion conditions (VC < 2,000) dominated on an annual basis. Approximately 62% of calculated hourly VC values fell in this category. Fair, good, and excellent dispersion conditions accounted for 18%, 9%, and 12% of hourly VC values, respectively. Ventilation over the city was poorer during winter, as expected. In this season, approximately 80% of the hourly VC values corresponded to poor dispersion conditions. Distribution of VC values was more even during summer season. Although 43% of the hourly VC values still corresponded to "poor" dispersion conditions, "fair," "good," and "excellent" accounted for 21%, 13%, and 23% of calculated VC, respectively.

Diurnal variation of VC in the summer and winter seasons are given in Fig. 9b. Ventilation coefficient showed well-defined diurnal patterns in both seasons. Ventilation was high during daytime, with a maximum between 1400 and 1800 hours and low at night. Patterns were similar in summer and winter, except winter daytime where VC values were significantly smaller than summer daytime values. The difference was a factor of two during morning hours and increased to a factor of five at 1800 hours. Nighttime VC values (between 2300 and 0600 hours) were approximately the same in both seasons.

During winter, average VC at all hours corresponded to "poor" dispersion conditions. Only between 1400 and 1600 hours did it approach to "fair" category. During the summer months, hourly average VC values were below 2,000 (poor ventilation) during night hours. However, "fair" ventilation prevailed between 0800 and 900 hours in the morning and 2200 and 2300 hours at night; "good" ventilation conditions prevailed between 1100 and 1300 hours in the morning and 2000–2100 hours at night; and "excellent" ventilation prevailed in the remainder of the day (1400–1900 hours). Observed diurnal pattern suggests that conditions in Ankara atmosphere are favorable for dispersion of pollutants in most of the daytime during the summer season. However, pollutants emitted during winter are not expected to be dispersed effectively. Variation in dispersion conditions, when coupled with higher space heating-related emissions in winter, can explain

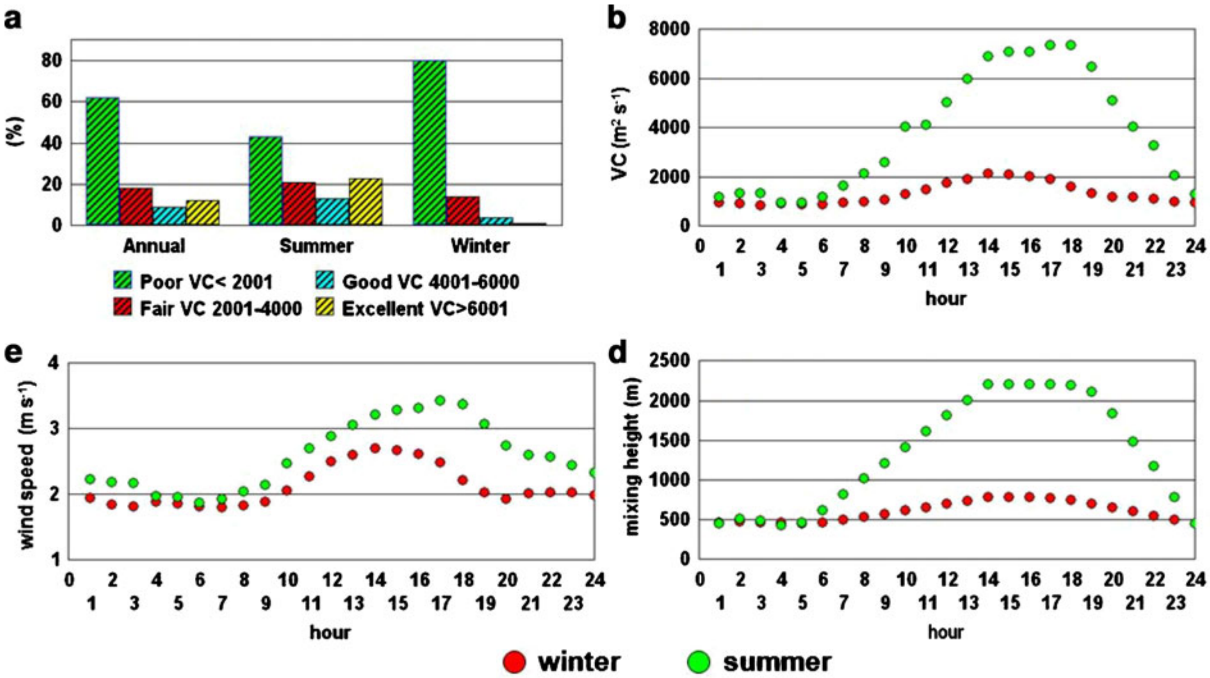


Fig. 9 Annual and seasonal frequency of occurrence of ventilation conditions in Ankara (**a**), diurnal variation of ventilation coefficient (**b**), wind speed (**c**), and urban mixing height (**d**)

pollution episodes which are frequently observed during the winter months.

The diurnal pattern observed in VC was due to diurnal variations in wind speed and mixing height, which are shown in Fig. 9c, d, respectively. Both parameters had higher values during daytime and higher values in summer. However, summer–winter difference in wind speed was not as pronounced as the difference in mixing height, indicating that observed large summer winter difference in VC was determined by changes in mixing height rather than changes in wind speed.

The effect of ventilation on concentrations of pollutants was demonstrated by comparing VC with API, which is a parameter calculated using air quality data. Comparison was performed for a period between October 1999 and March 2000 because API was calculated only for the winter season. Results are given in Fig. 10. The relation between API and VC was more obvious than the relations between measured concentrations of pollutants and wind speed or mixing height alone, which is discussed previously in the article. All high values of the API (poor air quality) corresponded to low values of VC (poor dispersion conditions), and all low values of the API (acceptable or good air quality) corresponded to high values of the VC (fair, good, or excellent dispersion conditions). This clearly demonstrates that when determining the air quality, vertical and horizontal displacement of pollutants is more important than variation in emissions. Although this statement was true for the general level of air quality in Ankara, it is not necessarily correct for individual stations because some of the stations such as

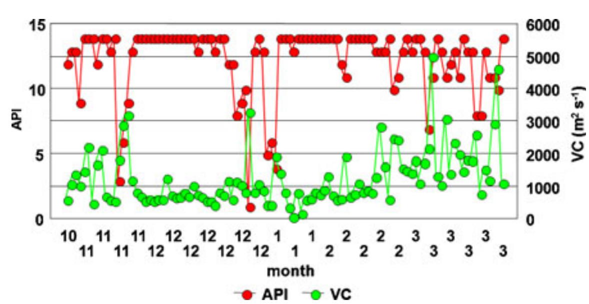


Fig. 10 The relation between API and VC in the period between October 1999 and March 2000

traffic ones were very close to emission sources, and the role of emissions was more important in explaining variability of pollutant concentrations than horizontal and vertical movements in the atmosphere. For example, the agreement observed between the station index obtained for traffic stations and VC was not as good as the agreement observed between VC and the city index.

Conclusion

Concentrations of conventional air pollutants, namely, CO, NO, NO_2, SO_2, and PM_{10}, were compared between traffic-impacted and residential stations. On an annual basis, PM_{10} concentrations were found to be similar in both station groups, while SO_2 concentrations were higher at traffic-impacted stations. Seasonal variations of both parameters showed that domestic heating was the dominating source of PM_{10} and SO_2 in both station groups in winter. Relatively low winter-to-summer ratio of SO_2 (1.0–1.8) concentration at traffic-impacted stations was attributed to contribution of diesel emissions. Lack of significant variation in winter-to-summer PM_{10} ratio, on the other hand, was attributed to enhanced resuspension of surface soil during the summer season.

PM_{10}-to-SO_2 and NO-to-NO_2 ratios showed statistically significant differences between traffic-impacted and residential stations. These ratios proved to be reliable tracers to differentiate between impacts of motor vehicle and space heating emission at a receptor.

An air pollution index was defined and calculated for Ankara and used to forecast the air quality expected in the next day. The agreement between calculated and predicted indices was comparable to those reported in literature.

Diurnal and seasonal variations in dispersion conditions were investigated using ventilation coefficient concept. Results of hourly VC calculations demonstrated that the dispersion conditions were poor in 80% of the time in winter and 43% of the time in summer. However, dispersion was found to be favorable during daytime in the summer season. An excellent inverse relation between the API and VC during the winter season indicated that the air quality in Ankara, during the winter season, was determined by meteorology rather than emissions.

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