



Spatial and temporal look at ten-years air quality of Istanbul city

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Abstract

This study is aimed to investigate spatial and seasonal variations of air pollutants in Istanbul between 2007 and 2017. Target air pollutants were carbon monoxide, particulate matter, sulfur dioxide, nitrogen oxides, and ozone. Air quality data of the city of Istanbul were obtained from 31 continuous air quality monitoring stations located at the Anatolian and the European Sides of the city. Spatial and temporal variations of the air pollutants were assessed by statistical methods ($p < 0.05$). According to the results of this study, all air pollutants showed seasonal variations and all parameters were found to be higher during the heating periods than other periods ($p < 0.05$), except for ozone. The annual average values of carbon monoxide, particulate matter with diameter of less than 10 μm , sulfur dioxide, ozone, and nitrogen dioxide (except for nitrogen dioxide levels measured in 2017) concentrations were below the national limit values in all stations between 2007 and 2017. In terms of yearly variation of the air pollutants, carbon monoxide and ozone showed statistically significant increasing trends ($p < 0.001$). Overall, once ten-years average air quality data were compared with current air quality limit values which was effective since 2019, PM and NO_2 may have limit exceedance problems in the next years. Moreover, levels of particulate matter with diameter of less than 2.5 μm were measured at 3 air quality monitoring stations, exceeded both World Health Organization and European Union limit values. Furthermore, positive correlations were found among the air pollutants ($p < 0.001$).

Keywords Air quality · Carbon monoxide · Istanbul · Nitrogen oxides · Ozone · Particulate matter · Sulfur dioxide

Abbreviations

AQMS	Air quality monitoring station
BTEX	Benzene, toluene, ethylbenzene, xylenes
CFR	Code of federal regulation
CO	Carbon monoxide
EU	European Union
F	Factor
HKDYY	Turkish air quality evaluation and management regulation
IB	Istanbul metropolitan municipality
MoE&U	Ministry of environment and urbanization
MTHM	Marmara clean air center
NO	Nitrogen monoxide
NO_2	Nitrogen dioxide
NO_x	Nitrogen oxides
O_3	Ozone

PM	Particulate matter
PM_{10}	Particulate matter with diameter of less than 10 μm
$\text{PM}_{2.5}$	Particulate matter with diameter of less than 2.5 μm
SO_2	Sulfur dioxide
TÜV	Technischer Überwachungsverein (International technical control company)
US EPA	United States Environmental Protection Agency
WHO	World Health Organization

Introduction

Air pollution issue in Turkey was mostly observed during the winter due to domestic fuel consumption, in addition to the pollution from the exhaust emissions that is increasingly becoming a threat. Mostly, potential sources of air pollutants are roughly categorized as point, area, and line sources to estimate emission inventory of a region. Thermal power plants, oil refineries, high-capacity factories, and organized industrial zones are assumed to be the major point pollutant

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sources. In addition, domestic heating for densely populated residential settings as area source, and roads due to traffic emissions are line sources (Altwickler et al. 1999). Nitrogen oxides (NO_x), sulfur dioxide (SO₂), particulate matter (PM), ozone (O₃), and carbon monoxide (CO) are the typical urban air pollutants regulated in most of the countries worldwide.

Briefly, NO_x is formed by the reaction of nitrogen (N₂) in the air with O₂ during high-temperature fuel combustion. SO₂ is produced when sulfur-containing fuels are burned or metals are extracted from sulfur-containing ore. In the US, about two-thirds of the emissions come from coal burning to generate electricity. CO is produced from incomplete combustion of fuels. In the US, more than half of the emissions consist of vehicles on the road. Although there is no direct source of tropospheric ozone, it is formed by a complex sequence of chemical reactions caused by sunlight. Particulate matter is not combinations of uniform compounds; some are acid, organic chemical, metal or soil. Some particles are formed by atmospheric reactions of gases such as in the case of SO₂ or NO₂. Particles with a diameter of 10 μm and smaller are considered as PM₁₀, and particles with a diameter of 2.5 μm and smaller are considered as PM_{2.5} (Mihelcic and Zimmerman 2010).

Istanbul is the most crowded city of Turkey (population in 2019 is 15.519.267 people) and the most crowded 13th metropolitan city of the world (World City Populations 2020). Istanbul's urbanization rate is above the average of Turkey. Contribution to Turkey's economy with the service sector is huge due to extensive industry, finance, trade, construction activities held in Istanbul. Istanbul is also in a central position in exports and imports and money markets are located here. In addition, Istanbul is an important city in terms of tourism (Ministry of Culture and Tourism 2019). In 2018, 13.4 million tourists visited to Istanbul, ranking the 8th most visited destination globally (Forbes 2019). Domestic heating, traffic (both road and marine traffics), and industry are the major components of the air pollution sources of Istanbul. Therefore, air quality of Istanbul city is crucial in terms of public health of the residents and the tourists visiting the city.

Earlier studies pointed out the importance of air pollution on Istanbul city as increase rate of population growth, rapid immigration, industrial activities without modern process control air pollution control measures, use of non-qualified fuel use, both road and marine traffic (Incecik 1986; Bozyazi et al. 2000; Unal et al. 2000, 2011; Sumen et al. 2005; Alkoy et al. 2009; Elbir et al. 2010; Çapraz et al. 2016, 2017; Baykara et al. 2019). Due to population it serves, sustaining a good air quality in Istanbul is crucial in terms of public health concerns. In addition to source contributors of air pollutants measured in Istanbul city, health effects of air pollution were estimated in other studies (Issever et al. 2005; Hapcioglu et al. 2006; Alkoy et al. 2009; Çapraz et al.

2016, 2017; Onat et al. 2019). Alkoy et al. (2009) estimated the epidemiological aspects of Istanbul air quality between 1994 and 1998. Influence of air pollution and meteorological parameters on respiratory diseases were investigated in two studies, covering data between 1997 and 2001 (Issever et al. 2005; Hapcioglu et al. 2006): Strong to moderate negative associations were found for chronic obstructive pulmonary disease admissions and SO₂, NO, CO, and PM₁₀, respectively (Hapcioglu et al. 2006). Acute coronary syndrome was positively associated with SO₂, CO, NO, and PM₁₀ levels (Issever et al. 2005). The linkage between air pollution and mortality between 2007 and 2012 and they found that SO₂ as the largest relative risk factor for death (Çapraz et al. 2016). A study, considering the association between health problems and PM_{2.5} and black carbon levels measured in Istanbul, found variable PM levels for different public transportation types (Onat et al. 2019).

The aims of this study are to investigate (1) spatial, (2) seasonal, (3) yearly, (4) ten-years variations of air pollutants (CO, NO, NO₂, NO_x, SO₂, O₃, PM_{2.5}, and PM₁₀) at all available air quality monitoring stations (AQMSs) in Istanbul between 2007 and 2017, (5) to estimate potential source contributors of the air pollutants, and (6) to determine the hot-spot locations that may have potential to exceed the national limit values of the air pollutants and require air quality improvement precautions in the near future.

Materials and methods

Study sites

Istanbul is the most crowded city of Turkey and currently 2904 people live in every km² of the city in terms of population density over the surface area. Population of Istanbul city was 12.573.836 in 2007 and 15.029.231 in 2017 (TÜİK 2018). It should be pointed out here that some towns and districts of Istanbul city have been split or combined with another district(s) over the years due to some planning reasons. Therefore, population dynamics could not have been compared pairwise from 2007 to 2007. The most populated 5 districts were Ümraniye (897.260), Kadıköy (744.670), Üsküdar (582.666), Kartal (541.209), and Esenler (517.235) in 2007 and Esenyurt (846.492), Ümraniye (699.901), Üsküdar (533.570), Sultangazi (528.514), and Kartal (463.433) in 2017, respectively (TÜİK 2018).

The air quality monitoring data used in the study were taken from the AQMSs of the national air quality monitoring network of the Ministry of Environment and Urbanization (MoE&U 2018). The gathered data covered a ten-year period (2007–2017) as daily average. Measurements of some air pollutants started in between the study period and number of air pollutants measured at the AQMSs and/



or number of AQMSs were increased particularly in 2013 by MTHM. Two AQMSs at different parts of Kagithane, Kandilli, Üsküdar, and Ümraniye districts were available, either established by Istanbul Municipality (those stations are coded as—IB) or MTHM (those stations are coded as—M). The total number of AQMSs in Istanbul was 31, where 18 stations were located on the European side and 13 stations were located on the Anatolian side of the city. Figure 1 shows the locations of the active air quality monitoring stations (AQMSs) in Istanbul throughout the study period. Of 31 AQMSs, PM₁₀ and NO–NO₂–NO_x were measured in 28 stations, O₃ was measured in 24 stations, SO₂ was measured in 23 stations, CO was measured in 22 stations, and PM_{2.5} was measured in 3 stations.

Air quality monitoring devices

As already mentioned, AQMSs of Istanbul were established first either by Istanbul Metropolitan Municipality or Marmara Clean Air Center and therefore provided devices for each AQMS were not the same. Also, dates of first establishment AQMSs and the further addition of air quality parameter(s) on the existing AQMSs were different for each station. Nevertheless, all devices that were established in all AQMSs over the study period were compatible with the internationally accepted corresponding standards and also calibration and maintenance was conducted on a regular basis (IBB 2020). All devices were monitoring the air quality continuously (24 h/7 days) and producing data as real-time. Time resolution of the measurements obtained by the instruments was 1 min. Brief explanations of the measurement techniques and the used measurement devices are as follows (more technical details can be found on the web sites of the corresponding instruments).

PM measurement devices (Enviorenment SA MP101M, Thermo 5014i, Metone Bam 1020, Environnement SA PM162M, MCZ LVS16, LECKEL SEQ 47/50, and MCV HVS1) were working according to the reference methods that were compatible with EN 12341 for PM₁₀ and EN 14907 for PM_{2.5}, and all the measurement techniques used in all devices were approved by US EPA as Federal equivalent methods. O₃ measurement devices (Environnement 0341 M–O342M–O342e, Thermo 49i, and Teledyne T400) were working with UV absorption principle, and they were compatible with ISO 13964, 2008/50/EC, EN 14625, EN 15267, US-EPA 40 CFR, sections 53 and 58. CO measurement devices (Environnement SA CO12M–CO12e, Thermo 48i, and Teledyne T300) were working with IR absorption principle, compatible with ISO 4224, EN 14626, EN 15267, US-EPA 40 CFR sections 53 SUB B and SUB C, and approved by TUV. NO_x measurement devices (Environnement SA AC32M–AC32e, Thermo 42i, and Teledyne T200) were working with chemiluminescence technology, compatible with

ISO 7996, EN 14211: 2005, and RoHS directive. SO₂ measurement devices (Environnement SA AF22M–AF22e, Thermo 43i, and Teledyne T100) are based on UV fluorescence measurement principle, compatible with ISO 10498, 2008/50/EC, EN 14212, EN 15267, and US-EPA 40 CFR sections 53 SUB B and SUB C.

All instrumentations used in the AQMSs were approved by TÜV. Calibration systems provided by MCZ Inc. (Germany) were used for regular calibration and required maintenance of the air quality monitoring devices (concentration adjustment, CMK5, CGM, catalytic gas treatment K15, NGM5, and Environics 6100 gas calibrator). Only calibrated and accurate measurement results that were shared publicly and were considered as a raw data. Afterward, all data gathered from the AQMSs were subjected to data evaluation stage before forming the final dataset that used in this study.

Data evaluation

Outlier detection and removing the incorrect measurement results were the main and time-consuming phase of the data evaluation to increase the data quality. Initially, measurement errors and “negative/zero” concentration data were eliminated from yearly data of each AQMS. For this aim, scatter plot and box-whisker plots were drawn for each annual air pollutant data of the AQMS concerned. After dealing with the outliers, 2.5–97.5% of the data set was assessed as the final form of the data set. Lastly, if fill factor of the air quality parameters at any station was over 50% for the year concerned, this data set was assumed to be appropriate for further statistical calculations. Thus, even though some air pollutants were measured at any of the stations, if the data quality of the year concerned did not fit the fill factor, this data set was not used in this study. Therefore, number of AQMS given in the previous section reduced after the data evaluation as given in Table 1, showing how many AQMS data for the calculations were used. Spearman rank correlation was used due to the nonlinear data representation. ANOVA test showed the differences among group means in a sample. For all applied tests, $p < 0.05$ was considered statistically significant. To estimate factors influencing the ambient air quality of Istanbul city, the multivariate factor analysis with varimax rotation was applied to the whole data set. Monthly average levels of the air pollutants measured throughout the study period were input and the first factor affected the air quality the most and the last factor affected the least as output of the factor analysis (Mentese et al. 2012, 2020a, b; Mentese and Akça 2020).



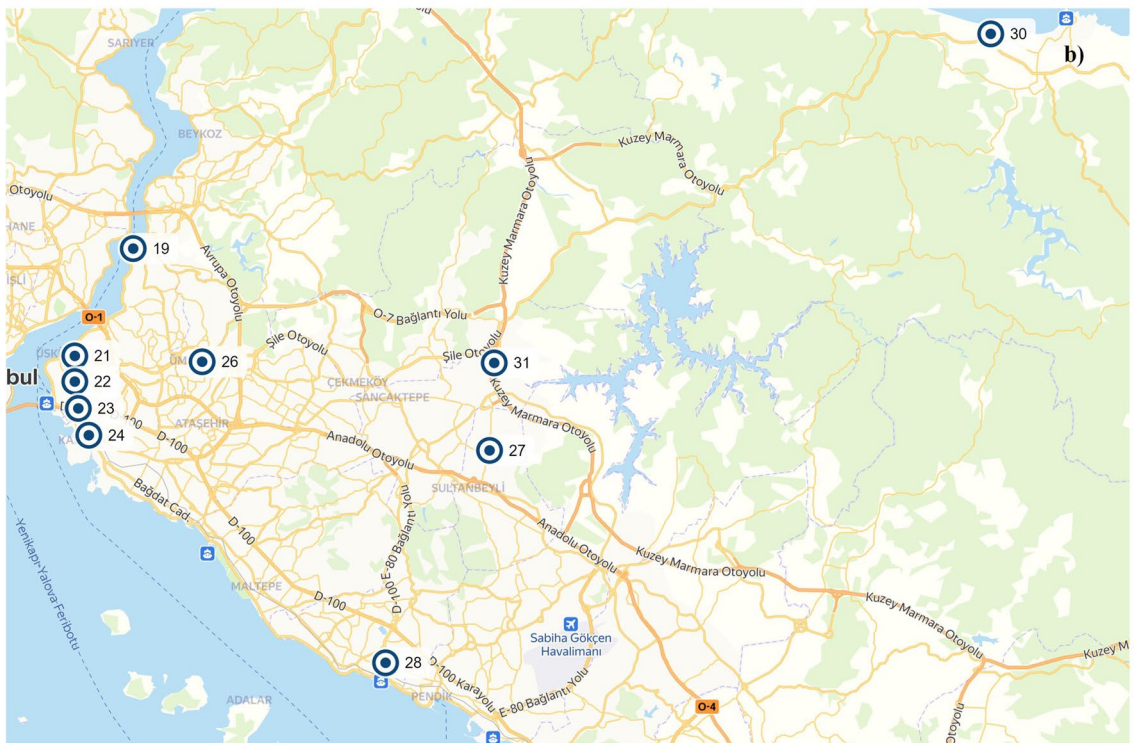
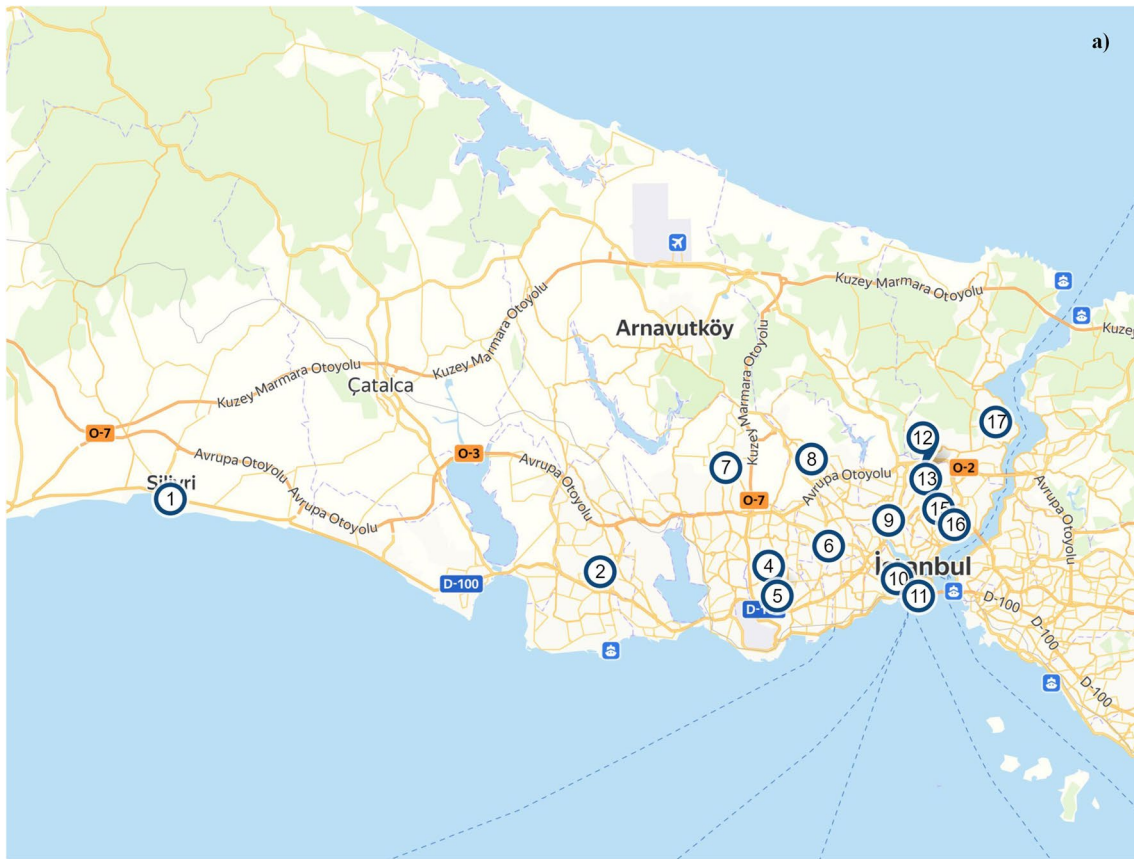


Fig. 1 Locations of air quality monitoring stations in Istanbul by 2017 stations on the **a** European side and **b** the Asian side (from left to right). ● (Locations 1: Silivri, 2: Esenyurt, 3: Avcilar, 4: Yenibosna, 5: Şirinevler, 6: Esenler, 7: Başakşehir, 8: Sultangazi, 9: Alibeyköy, 10: Aksaray, 11: Çatladikapi, 12: Kagithane-M, 13: Kagithane-IB, 14: Maslak, 15: Mecidiyeköy, 16: Beşiktaş, 17: Sarıyer, 18: Kumköy, 19: Kandilli-M, 20: Kandilli-IB, 21: Üsküdar-M, 22: Üsküdar-IB, 23: Selimiye-Üsküdar, 24: Kadıköy, 25: Göztepe, 26: Ümraniye-M, 27: Sultanbeyli, 28: Kartal, 29: Büyükkada, 30: Şile, 31: Ümraniye-IB)

Results and discussion

General view of Istanbul air quality

Average values of temperature and relative humidity throughout the study period were $15. \pm 7.1$ °C and $79 \pm 13.2\%$, respectively. Descriptive statistics for the measured air quality parameters of Istanbul between 2007 and 2017 are given in Table 1. Number of AQMSs were increased by MTHM as from 2013. NO_x and ozone were measured at the maximum number of stations ($n = 21$), whereas PM_{2.5} was measured at only 3 AQM stations as from 2017. Ten-years average levels of CO, PM_{2.5}, PM₁₀, SO₂, NO, NO₂, NO_x, and ozone from 2007 to 2017 were

851, 27, 53, 9, 51, 63, 122, and 34 µg/m³, respectively. No national limit value exceedance was observed for all parameters as a city average, except that annual average NO₂ level over the year of 2017. On the other hand, NO_x limit value (30 µg/m³) set in HKDYD effective as from 2014 to protect the vegetation was exceeded from 2014 to 2017 (HKDYD 2008).

CO levels

As can be seen from Table 1, the highest annual average CO level was observed recently, in 2017 (1497 µg/m³), whereas the lowest annual average CO level was observed in 2008 (618 µg/m³). Once all AQMSs data were considered over the study period to take a picture of CO levels occurred in Istanbul, it was seen that CO levels risen over the years ($p < 0.001$), indicating increasing the contributions of CO sources in the air. Figure 2a shows the spatial variation of CO concentrations throughout the study period. The highest CO levels were observed in Selimiye, Kagithane-IB, and Çatladikapi stations with a median CO level of > 1500 µg/m³, while median CO levels were below 1000 µg/m³ at the remaining AQMSs. The CO concentrations measured in Selimiye station varied in a very wide range (450–5150 µg/

Table 1 Descriptive statistics for the air quality of Istanbul city^a

Year	Air pollutant (µg/m ³)							
	CO	PM _{2.5}	PM ₁₀	SO ₂	NO	NO ₂	NO _x	O ₃
2007	917 ± 64 (9; 16000 ^b)	NA	67 ± 24 (10; 150)	13 ± 3 (9; 60)	42 ± 19 (6)	45 ± 9 (5; 100)	86 ± 16 (6)	24 ± 17 (3; 120 ^b)
2008	618 ± 121 (9; 16000 ^b)	NA	57 ± 14 (10; 150)	8 ± 3 (9; 60)	52 ± 21 (6)	69 ± 10 (5; 100)	116 ± 29 (6)	30 ± 11 (3; 120 ^b)
2009	652 ± 138 (9; 16000 ^b)	NA	54 ± 17 (10; 150)	10 ± 2 (9; 60)	55 ± 21 (6)	74 ± 25 (5; 100)	136 ± 34 (5)	26 ± 11 (4; 120 ^b)
2010	735 ± 242 (9; 16000 ^b)	NA	50 ± 10 (10; 132)	6 ± 1 (9; 52)	55 ± 25 (6)	74 ± 22 (5; 92)	125 ± 43 (6)	25 ± 21 (4; 120 ^b)
2011	739 ± 163 (9; 16000 ^b)	NA	48 ± 7 (10; 114)	9 ± 1 (9; 44)	51 ± 26 (6)	67 ± 15 (5; 84)	121 ± 50 (6)	25 ± 9 (4; 120 ^b)
2012	684 ± 49 (7; 16000 ^b)	NA	53 ± 12 (10; 96)	7 ± 1 (9; 36)	42 ± 22 (6)	67 ± 14 (5; 76)	125 ± 49 (6)	34 ± 8 (3; 120 ^b)
2013	733 ± 151 (12; 16000 ^b)	30 ± 7 (3)	57 ± 15 (19; 78)	7 ± 1 (17; 28)	48 ± 32 (9)	63 ± 23 (10; 68)	138 ± 106 (10)	48 ± 23 (17; 120 ^b)
2014	831 ± 572 (14; 16000 ^b)	29 ± 6 (3)	53 ± 14 (19; 60)	6 ± 3 (17; 20)	45 ± 33 (11)	58 ± 18 (11; 60)	125 ± 67 (9; 30^c)	41 ± 23 (19; 120 ^b)
2015	765 ± 505 (15; 14000 ^b)	26 ± 5 (3)	52 ± 14 (19; 56)	7 ± 3 (17; 20)	57 ± 35 (20)	54 ± 22 (13; 58)	124 ± 61 (21; 30^c)	38 ± 21 (21; 120 ^b)
2016	1187 ± 950 (14; 12000 ^b)	23 ± 4 (3)	48 ± 13 (19; 52)	20 ± 34 (15; 20)	49 ± 23 (20)	55 ± 18 (13; 56)	117 ± 56 (21; 30^c)	39 ± 19 (21; 120 ^b)
2017	1497 ± 1332 (14; 10000 ^b)	26 ± 2 (3)	46 ± 13 (19; 48)	11 ± 11 (17; 20)	61 ± 44 (20)	64 ± 29 (13; 54)	132 ± 14 (21; 30^c)	37 ± 22 (21; 120 ^b)
2007–2017	851 ± 265	27 ± 2	53 ± 6	9 ± 4	51 ± 6	63 ± 9	122 ± 14	34 ± 8

^aData were presented as arithmetic mean ± standard deviation of 2.5–97.5% of the stations’ annual average concentrations (number of station; available HKDYD limit value at the year concerned) in the table. ^b8-h average limit value. ^cNO limit value is set to protect the vegetation. Yearly average values that exceeded the HKDYD limit value of the year concerned are shown bold. NA: Not available

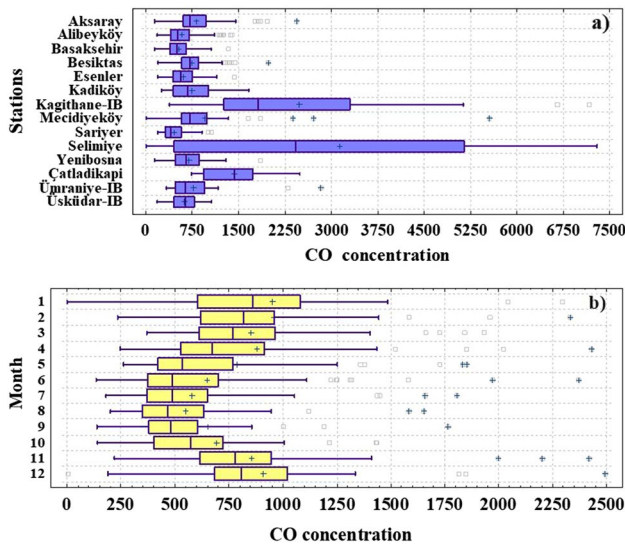


Fig. 2 CO concentrations ($\mu\text{g}/\text{m}^3$) measured **a** at AQMSs of Istanbul ($p < 0.001$) and **b** monthly variation between 2007 and 2017 ($p < 0.001$). (Note: designations of the boxes: \square : 25–75%, $|$ and $+$: lower and upper confidence levels within 1.5 inter quartile range (IQR), $|$: median line, and $+$: arithmetic mean)

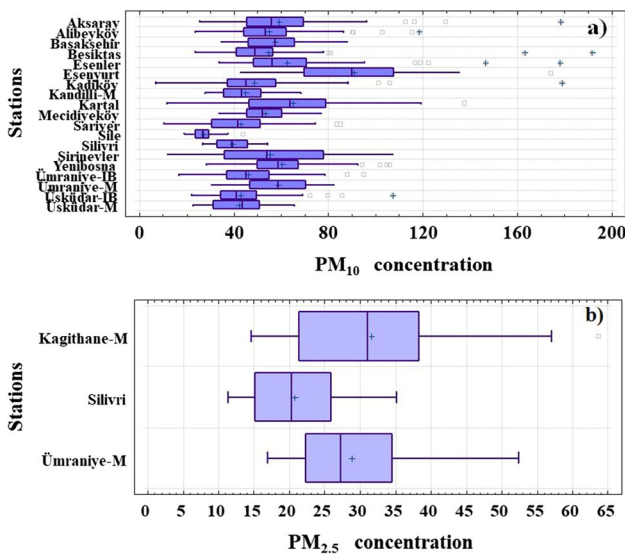


Fig. 3 **a** PM_{10} ($p < 0.001$) and **b** $\text{PM}_{2.5}$ ($p < 0.001$) concentrations ($\mu\text{g}/\text{m}^3$) measured at AQMSs of Istanbul between 2007 and 2017

m^3). According to ANOVA test, CO levels showed a statistically significant difference among the AQMSs ($p < 0.001$). In terms of yearly CO variation at each AQMS, Yenibosna, and Başakşehir stations had increasing trend, whereas Alibeyköy, Esenler, and Üsküdar-IB stations had decreasing trend over the years ($p < 0.05$). Furthermore, monthly variation of CO levels measured at all AQMSs throughout the study period is shown in Fig. 2b. Even though several extremely high CO levels up to $7000 \mu\text{g}/\text{m}^3$ were seen,

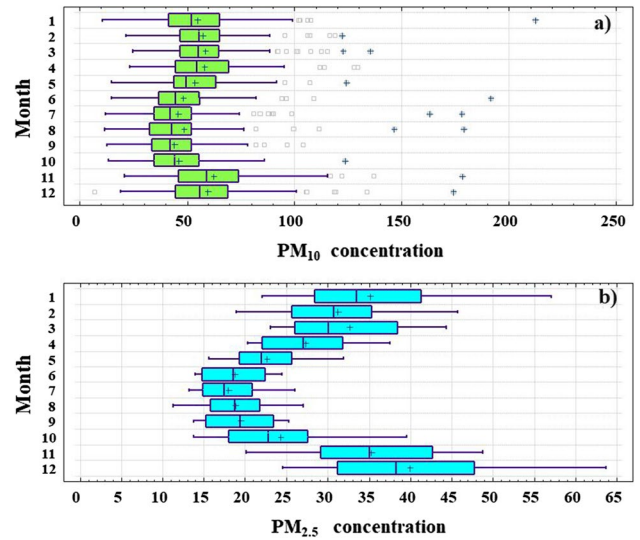


Fig. 4 Monthly variations of **a** PM_{10} ($p < 0.001$) and **b** $\text{PM}_{2.5}$ ($p < 0.001$) concentrations ($\mu\text{g}/\text{m}^3$) measured at all AQMSs of Istanbul between 2007 and 2017

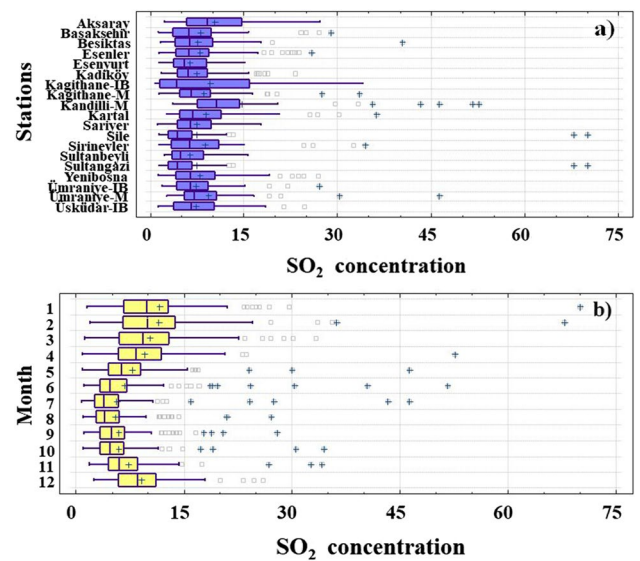


Fig. 5 SO_2 concentrations ($\mu\text{g}/\text{m}^3$) measured **a** at AQMSs of Istanbul ($p < 0.001$) and **b** monthly variation between 2007 and 2017 ($p < 0.001$)

to visualize monthly change of CO levels better, the concentration scale was shown up to $2500 \mu\text{g}/\text{m}^3$ in Fig. 2b. Accordingly, the highest CO levels were seen during the winter (med CO level was approx. $850 \mu\text{g}/\text{m}^3$), whereas the lowest CO levels were seen during the summer (med CO level was approx. $500 \mu\text{g}/\text{m}^3$). According to ANOVA test, CO levels showed a statistically significant monthly difference, based on monthly average CO levels data, covering

all AQMSs ($p < 0.001$). Both CO limit values set by Turkish Ministry (in HKDYY: 10 mg/m^3 as 8-h average) and United States Environmental Protection Agency (US EPA, 2020) ($9 \text{ ppm} = 10.3 \text{ mg/m}^3$) were not exceeded at any of the AQMS.

PM levels

According to Table 1, the highest annual average PM_{10} level was observed in 2007 (avg: $67 \text{ }\mu\text{g/m}^3$), whereas the lowest annual average PM_{10} level was observed in 2017 ($46 \text{ }\mu\text{g/m}^3$). It was seen that PM_{10} levels decreased over the years, once all AQMS data were considered over the study period and were negatively correlated with year ($p < 0.001$), indicating the source contributors of PM_{10} in the air were lowered. Figure 3a shows the spatial variation of PM_{10} throughout the study period. The highest PM_{10} level was observed in Esenyurt (median PM_{10} level was approx. $100 \text{ }\mu\text{g/m}^3$), which is the most crowded district of the city with a population of 846,492 people in 2017, while the lowest PM levels were seen in Şile (median PM_{10} level is approx. $30 \text{ }\mu\text{g/m}^3$), which was a rural touristic place occupied regularly with less people with a population of 35,131 people in 2017 (TÜİK 2018). According to ANOVA test, PM_{10} levels showed a statistically significant difference among the AQMSs ($p < 0.001$). In terms of PM_{10} variation at each AQMS over the years, Beşiktaş, Esenler, Kartal, Üsküdar-IB, Şile, Şirinevler, Ümraniye-M, and Üsküdar-M stations showed yearly decreasing trend ($p < 0.05$), while no significant increasing trend of PM_{10} was seen at the remaining AQMSs. Furthermore, monthly variation of PM_{10} levels measured at all AQMSs throughout the study period is shown in Fig. 4a. PM_{10} levels were slightly higher during the heating season (med PM_{10} level was approx. $60\text{--}65 \text{ }\mu\text{g/m}^3$) than the summer months (med PM_{10} level was approx. $50 \text{ }\mu\text{g/m}^3$). According to ANOVA test, PM_{10} levels showed a statistically significant monthly difference ($p < 0.001$). The fact that national PM_{10} limit values given in HKDYY were not constant for the study period (i.e., annual average PM_{10} limit value decreased in 2007 from 150 to $48 \text{ }\mu\text{g/m}^3$ in 2017), the annual average values were compared with the limit value of the year concerned (see Table 1 for HKDYY limit values), and annual PM_{10} limit values were not exceeded during the study period. On the other hand, the annual average PM_{10} values measured at all stations exceeded the current annual average PM_{10} limit value of $40 \text{ }\mu\text{g/m}^3$, which has been effective in HKDYY since 2019.

$\text{PM}_{2.5}$ has been measured since 2013 only at 3 AQMSs, which are Kagithane-M, Ümraniye-M, and Silivri AQMSs. As can be seen from Table 1, the highest annual average $\text{PM}_{2.5}$ level was observed in 2013 ($30 \text{ }\mu\text{g/m}^3$), whereas the lowest annual average $\text{PM}_{2.5}$ level was observed in 2016 ($23 \text{ }\mu\text{g/m}^3$). Once data of all 3 AQMSs were considered over

the study period, decrease in $\text{PM}_{2.5}$ levels was found over the years ($p < 0.05$), indicating the reduction of the source contributors of $\text{PM}_{2.5}$ emitted in the air. Figure 3b shows the spatial variation of $\text{PM}_{2.5}$ throughout the study period. The highest $\text{PM}_{2.5}$ levels were observed in Kagithane-M, Ümraniye-M, and Silivri stations, in descending order. Also, $\text{PM}_{2.5}$ concentration measured in Kagithane-M station varied in a very wide range ($15\text{--}64 \text{ }\mu\text{g/m}^3$). $\text{PM}_{2.5}$ levels showed a statistically significant difference among the AQMSs ($p < 0.001$). In terms of yearly $\text{PM}_{2.5}$ variations at each AQMS, merely Ümraniye-M station showed a decreasing trend over the years ($p < 0.05$), while no significant yearly variation was seen in both Kagithane-M and Silivri stations ($p < 0.05$). Furthermore, monthly variation of $\text{PM}_{2.5}$ levels measured at all 3 AQMSs throughout the study period is shown in Fig. 4b, indicating higher $\text{PM}_{2.5}$ levels occurrence during heating season (med $\text{PM}_{2.5}$ level was approx. $> 30 \text{ }\mu\text{g/m}^3$) and lower $\text{PM}_{2.5}$ levels occurred during the summer months (med $\text{PM}_{2.5}$ level was approx. $20 \text{ }\mu\text{g/m}^3$). According to ANOVA test, $\text{PM}_{2.5}$ levels measured at all AQMSs showed a statistically significant monthly difference ($p < 0.001$). The fact that no limit value has been set for ambient $\text{PM}_{2.5}$ levels on a national basis, annual $\text{PM}_{2.5}$ limit values stated by European Union (EU 2016) ($25 \text{ }\mu\text{g/m}^3$) and World Health Organization ($10 \text{ }\mu\text{g/m}^3$) (WHO, 2018) can be used just for making a comparison with the measured $\text{PM}_{2.5}$ levels. Accordingly, annual average $\text{PM}_{2.5}$ levels measured at 3 stations exceeded the WHO limit in each year, while they were below or slightly higher than EU's $\text{PM}_{2.5}$ annual limit value. Finally, there is an urgent need to increase the number of stations for $\text{PM}_{2.5}$ measurements in Istanbul city, particularly at the districts where air quality can be influenced by traffic and other combustion emission sources. Ambient $\text{PM}_{2.5}$ levels were found to be as high as $> 120 \text{ }\mu\text{g/m}^3$ in Palestine (Jodeh et al. 2020).

SO₂ levels

According to Table 1, the highest annual average SO_2 level was observed in 2016 ($20 \text{ }\mu\text{g/m}^3$), whereas the lowest annual average SO_2 level was observed in 2010 and 2014 ($6 \text{ }\mu\text{g/m}^3$). Once all AQMS data were considered over the study period, SO_2 levels showed no significant change by year ($p > 0.05$), indicating stable source contributors of SO_2 in the air over the years. Figure 5a shows the spatial variation of SO_2 levels throughout the study period. The SO_2 levels were mostly lower than $15 \text{ }\mu\text{g/m}^3$ at the AQMSs and the highest SO_2 levels were observed in Kagithane-IB and Kandilli-M stations. Also, the SO_2 concentrations measured in the Kagithane-IB station varied in a very wide range (range: $35 \text{ }\mu\text{g/m}^3$). SO_2 levels showed a statistically significant difference among the AQMSs ($p < 0.001$). In terms of yearly SO_2 concentrations at each AQMS, Sariyer, Başakşehir, Kagithane-M, Kandilli-M,

Şile, Şirinevler, and Ümraniye-M stations showed increasing trends, while Beşiktaş, Esenler, Kartal, Kagithane IB, Yenibosna, Üsküdar-IB, and Sultangazi stations showed decreasing trend over the years ($p < 0.05$). Furthermore, monthly variation of SO_2 levels measured at all AQMSs throughout the study period is shown in Fig. 5b. Even though several extreme SO_2 levels up to $70 \mu\text{g}/\text{m}^3$ were seen, the highest SO_2 levels occurred during the heating season, whereas the lowest SO_2 levels occurred during the summer, as expected. SO_2 levels showed a statistically significant monthly difference, based on monthly average SO_2 levels data of all AQMSs ($p < 0.001$). The fact that national SO_2 limit values given in HKDYY were not constant for the study period (i.e., annual average SO_2 limit value decreased in 2007 from 60 to $20 \mu\text{g}/\text{m}^3$ in 2017), the annual average values were compared with the limit value of the year concerned (see Table 1 for HKDYY limit values) and annual SO_2 limit values were not exceeded during the study period.

NO, NO_2 , and NO_x levels

As shown in Table 1, the highest annual average NO level was observed recently in 2017 ($61 \mu\text{g}/\text{m}^3$), whereas the lowest annual average NO level was observed in 2007 and 2012 ($42 \mu\text{g}/\text{m}^3$). Once all AQMS data were considered over the study period, NO levels showed no significant change over the years ($p > 0.05$). NO levels showed a statistically significant difference among the AQMSs ($p < 0.001$). In terms of yearly NO variation at each AQMS, Aksaray, Beşiktaş, Ümraniye-IB, and Kagithane-M stations showed increasing trends ($p < 0.05$), while NO levels did not decrease at the

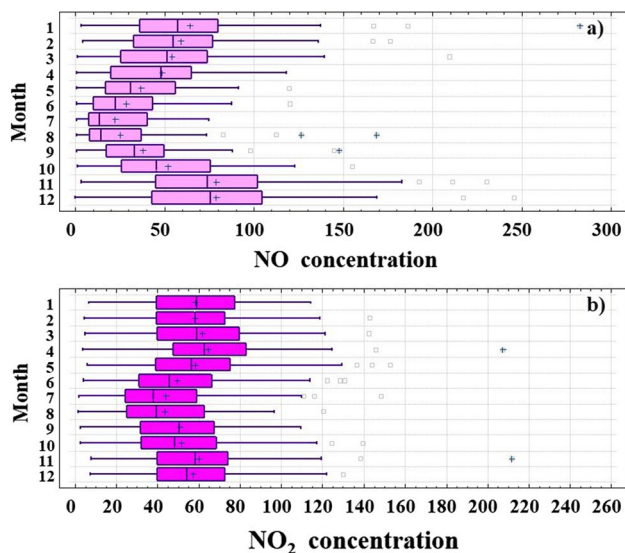


Fig. 6 Monthly variations of **a** NO ($p < 0.001$), **b** NO_2 ($p < 0.001$), and **c** NO_x ($p > 0.5$) concentrations ($\mu\text{g}/\text{m}^3$) measured at all AQMSs of Istanbul between 2017

remaining stations ($p > 0.05$). Furthermore, monthly variation of NO levels measured at all AQMSs throughout the study period is shown in Fig. 6a. The highest NO levels were seen during the heating season (med NO level was approx. $80 \mu\text{g}/\text{m}^3$), whereas the lowest NO levels were seen during the summer (med NO level was approx. $< 50 \mu\text{g}/\text{m}^3$). NO levels showed a statistically significant monthly difference, based on monthly average NO levels data of all AQMSs ($p < 0.001$).

According to Table 1, the highest annual average NO_2 level was observed in 2009–2010 ($74 \mu\text{g}/\text{m}^3$), whereas the lowest annual average NO_2 level was observed in 2007 ($45 \mu\text{g}/\text{m}^3$). Once all AQMS data were considered over the study period, NO_2 levels showed a decreasing trend over the years ($p < 0.001$). NO_2 levels showed a statistically significant difference among the AQMSs ($p < 0.001$). In terms of yearly NO_2 variation at each AQMS, Beşiktaş, Çatladikapi, Kagithane-IB, and Ümraniye-IB stations showed increasing trends ($p < 0.05$), while Esenyurt-M, Mecidiyeköy, Sultangazi, and Ümraniye-M showed decreasing trend over the years ($p < 0.05$). Furthermore, monthly variation of NO_2 levels measured at all AQMSs throughout the study period is shown in Fig. 6b. NO_2 levels were lower in the summer months than rest of the year and NO_2 levels showed a statistically significant monthly difference ($p < 0.001$). According to NO_2 limit values set in HKDYY for each study year, no limit exceedances were observed throughout the study period (i.e., NO_2 limit value was lowered in 2007 from 100 to $54 \mu\text{g}/\text{m}^3$ in 2017). However, currently effective NO_2 limit value of $40 \mu\text{g}/\text{m}^3$ set in HKDYY would have been exceeded.

As given in Table 1, the highest annual average NO_x level was observed in 2013 ($138 \mu\text{g}/\text{m}^3$), whereas the lowest annual average NO_x level was observed in 2007 ($86 \mu\text{g}/\text{m}^3$). Once all AQMS data were considered over the study period, NO_x levels showed no significant change over the years ($p > 0.05$), indicating constant source contributors of NO_x in the air over the years. Figure 7 shows the spatial variation of NO_x levels throughout the study period. The highest NO_x levels were observed in Aksaray and Beşiktaş. Also, the NO_x concentration measured in

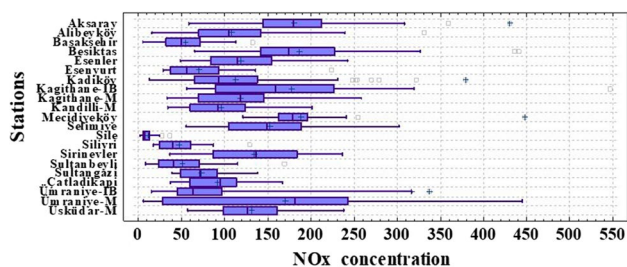


Fig. 7 NO_x concentrations ($\mu\text{g}/\text{m}^3$) measured at AQMSs of Istanbul between 2007 and 2017 ($p > 0.05$)

Ümraniye-M station varied in a very wide range. NO_x levels showed no statistically significant difference among the AQMSs ($p > 0.05$). Moreover, in terms of yearly NO_x variation at each AQMS, Aksaray, Alibeyköy, Beşiktaş, Esenler, Başakşehir, Esenyurt-M, and Ümraniye-M stations had increasing trends ($p < 0.05$), while Mecidiyeköy and Sultangazi had decreasing trends over the years ($p < 0.05$). Furthermore, monthly variation of NO_x levels measured at all AQMSs throughout the study period is shown in Fig. 6c. Even though the highest NO_x levels were observed during the heating season and the lowest NO_x levels were observed during the summer months. NO_x levels showed no statistically significant monthly difference, based on monthly average NO₂ levels data of all AQMSs ($p > 0.05$).

O₃ levels

According to Table 1, the highest annual average ozone level was observed in 2013 (48 µg/m³), whereas the lowest annual average ozone level was observed in 2007 (24 µg/m³). Ozone levels measured at all AQMS data rose over the study period were positively correlated with year ($p < 0.001$), indicating the increment of ozone source contributors in the air. As shown in Fig. 8a, ozone levels showed statistically significant difference among the AQMSs ($p < 0.001$). The highest ozone levels were observed in Ümraniye-M, Kandilli-M, Üsküdar-M, and Şirinevler stations with median ozone level of > 900 µg/m³, while median ozone levels were below 100 µg/m³ at the remaining AQMSs. In terms of yearly variation of ozone level at each AQMS, increasing trends were seen at Aksaray, Alibeyköy, Kandilli-M, Ümraniye-M, and Üsküdar-M, while decreasing trends were observed at Beşiktaş, Esenyurt, Sultanbeyli, and Şile stations over the years ($p < 0.05$). Furthermore, monthly variation of ozone levels measured at all AQMSs throughout the study period is shown in Fig. 8b. Even though several extreme ozone values up to > 500 µg/m³ were seen, the concentration scale was shown up to 500 µg/m³, to visualize monthly change better. Although ozone levels started to increase with spring and decreasing trend started with the fall season and varied in a very wide range over the months, monthly variation of ozone levels was not significant ($p > 0.05$). Earlier studies have already shown that there is a positive correlation between ozone levels and temperature (Zhang et al. 2015; Rao and Zurbenko 1994). A study conducted in Istanbul between 2007 and 2009 found minimum ozone levels during the winter period (Im et al. 2013). Since national limit value of 120 µg/m³ for an annual average ozone concentration is available 8-h average ozone limit value set by both Turkish Ministry and EU can be used for comparison and average ozone levels did not exceed this value at any of the AQMS.

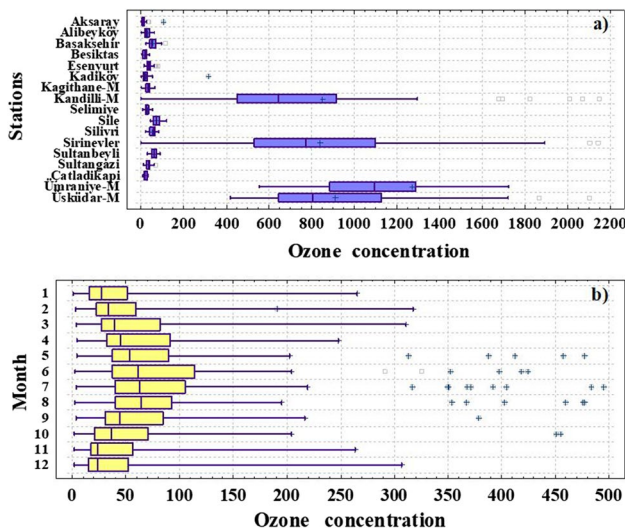


Fig. 8 Ozone concentrations (µg/m³) measured **a** at AQMSs of Istanbul ($p < 0.001$) and **b** monthly variation ($p > 0.05$) between 2007 and 2017

Table 2 Correlations across the monthly average air pollutant level pairs for all AQMSs data

Parameter	CO	NO	NO ₂	NO _x	O ₃	PM ₁₀	PM _{2.5}	SO ₂
CO	1							
NO	0.25** (682)	1						
NO ₂	0.03 (726)	0.55** (1069)	1					
NO _x	0.01 (683)	0.07* (1056)	0.05 (1069)	1				
O ₃	-0.14 (337)*	0.16** (610)	0.22** (848)	0.16** (609)	1			
PM ₁₀	0.16** (936)	0.21** (926)	0.10** (1123)	0.01 (933)	0.01 (669)	1		
PM _{2.5}	NA	0.52** (81)	0.40** (146)	0.31* (85)	0.09 (145)	0.81** (97)	1	
SO ₂	0.17** (780)	0.10* (825)	0.09* (1015)	0.05 (824)	0.18** (614)	0.10** (1316)	-0.04 (97)	1

Data in the table is presented as correlation coefficient (n); correlation coefficient of > 0.50 are shown bold. * $p < 0.05$ and ** $p < 0.001$ show significantly correlated pairs. NA: not available

Associations between the air pollutants and potential source contributors

Table 2 shows correlations between the measured air pollutants levels at all AQMSs throughout the study period. Strong correlations ($p < 0.001$) were found between PM_{10} and $PM_{2.5}$ ($r = 0.81$), between NO and NO_2 ($r = 0.55$), between NO and $PM_{2.5}$ ($r = 0.52$), and between NO_2 and $PM_{2.5}$ ($r = 0.40$). Also, moderate to weak correlations were found between several air pollutants ($p < 0.05$), such as NO_x and $PM_{2.5}$, CO and NO, NO_2 and O_3 , and NO and PM_{10} .

Table 3 shows factor analysis results for Istanbul city ambient air quality. Factor loadings and variance apportionments obtained by factor analysis with varimax rotation for components of ambient air quality is presented. $PM_{2.5}$ and NO_x levels are discarded from the dataset to be applied factor analysis. Since $PM_{2.5}$ has been measured merely at three AQMSs, number of pairwise data would be low. Levels of NO and NO_2 are used to explain nitrogen oxides sources. Based on the results of the factor analysis, 3 factors were identified, impacting the ambient air quality of Istanbul. The first factor (F1) was originated from traffic sources. F1 included high loadings of NO_2 and NO as well as moderate loading of ozone, indicating that this factor had contribution of traffic-related human activities (Beelen et al. 2013). The second factor (F2) was defined as combustion from mixed sources. F2 included high loading of CO and moderate loadings of PM_{10} , SO_2 , and NO. As already known, CO as the major source contributor of the second factor in an incomplete combustion product. Major sources of combustion in Istanbul are traffic, industry, and domestic heating with solid fuel. Besides, PM_{10} contribution together with CO presence in the same factor support this conclusion as PM_{10} might have originated from the same source contributor(s). The third factor (F3) was identified as heating and ozone accumulation, including high loadings of SO_2 and ozone levels. According to Istanbul city report published in 2015, solid fuel (coal including 0.9–2.0% Sulfur) and fuel oil provided as bunker fuel (majority of supplied fuel oil > 1% Sulfur) have been used in residential and industrial settings, in addition to natural gas consumption (MoE&U 2015). As already known, Bosphorus strait splitting the city to European and

Asian part is one of the busiest sea ways of the world with on average 50 000 transit ships passages (Ministry of Transport 2018). Turkey plays an important strategic role in maritime transport since the country is surrounded on three sides by the sea and located between Asia and Europe. Therefore, air pollution from ships is one of the major issues for Turkey. Previous studies showed the contribution of maritime transport on levels of air pollutants such as PM, SO_2 , NO_x , and hydrocarbon emissions (Mentese and Akça 2020; Kılıç and Deniz 2010; Alver et al. 2018).

In a study conducted in Istanbul, five source components for PM were identified: traffic, road dust, industry, and coal and gasoline combustion and industrial (Onat et al. 2012). Another study, considering ozone, BTEX, NO_2 , and SO_2 levels at 10 different urban points of Istanbul urban area between 2011 and 2012 found more source contributors (industrial and traffic related) other than a single source (Ercan et al. 2019).

Previous studies, starting from 90's up to now have indicated that the importance of air pollution issue for Istanbul city is still of concern in terms of public health (Saral 2011; Ozcan 2012; Unal et al. 2011; Kocak et al. 2011; Toros et al. 2013; Yurtseven et al. 2018; Elbir et al. 2010; Ercan et al. 2019; Gokce et al. 2020; Flores et al. 2017, 2020; Onat et al., 2019; Im et al. 2013; Ozdemir et al. 2014; Baykara et al. 2019; Ercan et al. 2019; Sahin et al. 2020). In the 1990s, high values for SO_2 and PM values were seen with the use of coal, and currently, low-quality fuel use in residential areas, industrial emissions, and vehicle emissions was shown as the causes of air pollution in Istanbul (Saral 2011). Anthropogenic air pollution emissions in Istanbul from residential combustion, solvent use, industry, fuel distribution, road and maritime transport, waste, and energy were evaluated together with other megacities in the Eastern Mediterranean and regional and long range air pollution transport found to have an importance in these cities (Kanakidou et al. 2011). Another study considered the maximum concentration values of SO_2 and NO_2 for Alibeyköy and Ümraniye stations by a numerical method (Ercelebi and Toros 2009). A GIS-based decision support system for urban air quality management for the year 2007 was prepared, and primary sources of SO_2 were estimated as industrial activities and traffic appeared

Table 3 Factor loadings^a and variance apportionments obtained by factor analysis with varimax rotation for components of ambient air quality of Istanbul city

Factor—potential source	Contributors (factor loadings)	Variance explained (%)
Istanbul city air quality		68.3
F1—traffic	NO_2 (0.87), NO (0.82), ozone (0.36)	30.6
F2—combustion (mixed sources)	CO (0.82), PM_{10} (0.55), SO_2 (0.32), NO (0.31)	20.5
F3—heating and ozone accumulation	SO_2 (0.85), ozone (0.65)	17.2

Monthly average concentration values of all AQMSs over the study period were used as input of the factor analysis. ^aLoadings > 0.30 are given in the table, loadings > 0.7 are shown in bold. F1–F3: factors 1–3

the major source of NO_x and CO (Elbir et al. 2010). Another study estimated CO₂ emissions from urban passenger transportation of Istanbul (Batur et al. 2019). Gokce et al. (2020) investigated the exterior air quality of Eurasia Tunnel and even though an increase in NO₂ concentrations after tunnel operations was observed, no limit exceedance was estimated from the national legislation. In a study, the contribution of residential heating in Istanbul urban air quality for CO, SO₂, NO_x, and PM₁₀ was estimated (Baykara et al. 2019). It was found that proportion of residential heating particularly in winter time emission inventory data was not negligible. It was found in another study that PM₁₀, SO₂, and CO levels were higher in the European side than Asian side of the city, on the basis of measurement results from 2003 and 2013 (Yurtseven et al. 2018).

Hot-spots suffering from air pollution

Current HKDYY limit values which have been effective since January 1, 2019 are as follows: annual average SO₂ level is 20 µg/m³, annual average NO₂ levels is 40 µg/m³, annual average PM₁₀ levels is 40 µg/m³, 8-h average CO level is 10 mg/m³, 8-h average O₃ level is 120 µg/m³, and annual average NO_x levels is set as 30 µg/m³ to protect the vegetation.

Among those air pollutants, PM and NO₂ levels appeared to pose problems in the next years for city of Istanbul in terms of sustaining the good air quality conditions to meet the requirements of national legislation. Thus, in this study, it was focused on NO₂ and PM₁₀ levels in the last 3 years of the study period (2015–2017) to predict the potential hot-spot destinations that may have poor air quality in the near future, because more attempts need to improve the air quality at those regions not to exceed the national limit values. As can be seen from Fig. 9, 3-yr average PM₁₀ levels exceeded the current annual PM₁₀ limit value in all stations and high values were found in Esenyurt, Aksaray, Yenibosna, and Başakşehir, in descending order. As already mentioned earlier, Esenyurt is the most populated district of the city and new construction projects, mostly for residential settings have increased in the last decade. National house sale statistics for Istanbul city recorded that on average 240,000 houses were sold annually and almost half of them were the new houses bought by the first owner (TÜİK 2020). Also, a total of 5.4 million houses are available in Istanbul city in 2017 and approximately 11% of them are new big-residential housing projects by TOKI and other companies (EVA 2020).

NO₂ levels exceeded the current annual NO₂ limit value in most of the AQMSs and high concentrations were found in Beşiktaş, Mecidiyeköy, Çatladıkapı, and Aksaray, in a descending order. The main common points of those districts are having very dense traffic load and populated with human activities throughout the day. Shopping,

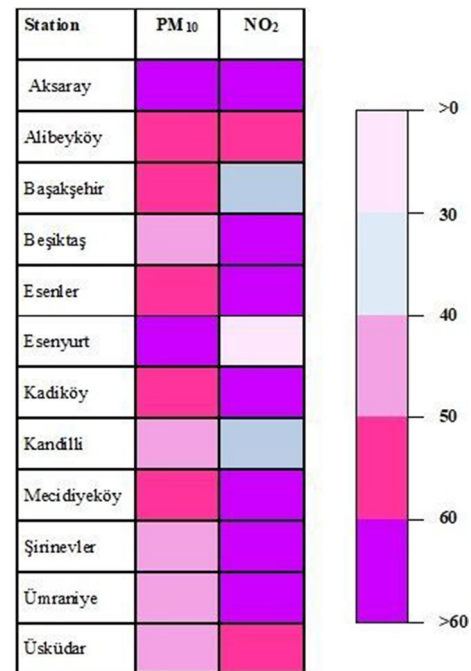


Fig. 9 Heat map for 3-years average PM₁₀ and NO₂ concentration at the AQMSs between 2015 and 2017

touristic, and cultural activities are held, and all types of transportation systems such as buses, tramway, subway, and ferry lines are used by many people around those districts. Also, both NO₂ and PM₁₀ levels were above 60 µg/m³ in Aksaray, located in the middle of the traffic junctions where many tramway, subway, and bus connection lines have transfer stop there.

In another study, impact of air pollution on respiratory hospital admissions between 2013 and 2015 was examined (Çapraz et al. 2017). Similar to our results, PM and NO₂ were responsible from the air pollution of Istanbul city, increasing the respiratory risk and hospital admissions.

The latest environmental status report for the Province of Istanbul published in 2018 indicated several outcomes, parallel to the results of this study observed that low levels of SO₂ were as a result of natural gas use for heating purposes; the highest SO₂ levels were observed in Kandilli where no industrial activity and traffic density were observed, but Kandilli is the berth for the ships passing over the Bosphorus, indicating the contribution maritime traffic; PM₁₀ levels exceeded the limit values particularly in the regions where urbanization was boosted such as Esenyurt, lead to increase in traffic density and industrial activities, and rise in PM₁₀ levels in Esenyurt, Başakşehir, Mecidiyeköy, Şirinevler, Ümraniye, Üsküdar were linked with the increased density of traffic (MOE&U 2018).



Conclusion

This study is aimed to investigate spatial and seasonal variations of air pollutants in Istanbul between 2007 and 2017. All air pollutants showed seasonal variations and all parameters were found to be higher during the heating periods than other periods ($p < 0.05$), except for ozone. CO and ozone showed statistically significant increasing trends over the years ($p < 0.001$). Also, once ten-years average air quality data were compared with current air quality limit values which was effective since 2019, PM and NO₂ may have limit exceedance problems in the next years. PM_{2.5} levels exceeded both WHO and EU limit values.

Overall, in terms of data quality, the data acquisition rates of the stations established for air quality measurements must be regular. Also, all air quality parameters are not measured at all stations. Moreover, the number of air quality measurement stations should be increased in terms of shifted population dynamics around new industrial settlements and districts with new housing projects. For instance, additional stations should be placed in and/or on the way through the new Istanbul airport, considering that the population and traffic will increase around there in the near future. Also, the fact that PM and NO_x emissions coming from traffic appeared to be the most important source of air pollution in Istanbul, specific measures to decrease traffic load over the city would improve the air quality such as park and ride, planning more bicycle ways, optimization of public transportation systems. Moreover, marine and airway emissions should be considered in the future plans and emission inventory of the city, since Istanbul is one of the most used transit region by both airlines and ships.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Ethical approval This article does not contain any studies with human participants or animals performed by any of the authors.

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