# A holistic approach to the air quality of Konya City, Turkey

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## Abstract

Considering an integrated approach to assess all of the measured pollutants in a diurnal, monthly, seasonal, and annual time scales and understanding the mechanisms hidden under low air quality conditions are essential for tackling potential air pollution issues. Konya, located in central Anatolia, is the largest province of Turkey with a surface area of 40,838 $km^2$ and has different industrial activities. The lack of recent detailed studies limits our information on the underlying air pollution levels in Konya and obscuring policymakers to develop applicable mitigation measures. In this study, we used hourly monitored air quality data of CO, $NO_2$, $NO_x$, $PM_{10}$, $PM_{2.5}$, and $SO_2$ from five stations in Konya and investigated the temporal and spatial variabilities for the 2008–2018 period via statistical analysis. Upon analysis, particulate matter was found to be the dominant pollutant deteriorating the air quality of Konya. The highest 2008–2018 periodic mean value of $PM_{10}$ was found in Karatay Belediye as 70.5 $\mu g/m^3$, followed by 67.4 $\mu g/m^3$ in Meram, 58.7 $\mu g/m^3$ in Selçuklu, and 43.7 $\mu g/m^3$ in Selçuklu Belediye. The 24-h limit value of $PM_{10}$ given as 50 $\mu g/m^3$ in the legislation was violated in all of the stations, mainly during winter and autumn. High positive correlations were found among the stations, and the highest correlation was obtained between Selçuklu Belediye and Karatay Belediye with a Pearson correlation coefficient of 0.77. Long-term data showed a decreasing trend in $PM_{10}$ concentrations. Diurnal variability is found to be more pronounced than weekly variability. For almost all of the pollutants, except for photochemical pollutants like $O_3$, a prominent result was the nighttime and morning rush hours high-pollutant levels. A case study done for the January 29, 2018 to February 05, 2018 episode showed the importance of meteorology and topography on the high levels of pollution. Limitation of the pollutant transport and dilution by meteorological conditions and the location of Konya on a plain surrounded by high hills are believed to be the main reasons for having low air quality in the region.

**Keywords** Integrated air quality assessment · Emission sources · Air pollution meteorology · Konya City

## Introduction

Air pollution is the presence of material (i.e., chemicals) in the air with quantities and lifetime enough to produce harmful effects. Rising levels of these unwanted chemicals (i.e., pollutants) decrease the quality of the air we breathe. The dose intake is considered as the concentration of pollutants breathed over a certain time period, also expressed as exposure period, high enough that results in adverse health effects (De Nevers 2017). Air pollution may also cause esthetic impacts like visibility reduction in the form of brown or blue haze together with unpleasant smells. Low visibility caused by air pollution may also lead to accidents in various transportation means (e.g., terrestrial, aviation, maritime, etc.).

From smog over cities to smoke inside the home, air pollution poses a major threat to health and climate. The combined effects of ambient (outdoor) and household (indoor) air pollution cause about seven million deaths every year, largely as a result of increased mortality from stroke, heart disease, chronic obstructive pulmonary disease, lung cancer, and acute respiratory infections (WHO, 2020). World Health Organization (WHO) data shows that nine out of ten people breathe air that exceeds WHO guideline limits containing

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high levels of pollutants, with low- and middle-income countries suffering from the highest exposures.

Air quality, like the weather, may change from day to day, hour to hour, or instantaneously, depending on emissions and meteorological conditions. Meteorological parameters play a significant role in determining air pollutant concentrations (Zhou et al. 2020). Decreases in PM concentrations were observed with increases in precipitation rate and wind speed (Galindo et al. 2009). Weather systems associated with low wind speeds and inversion showed an effect on the elevated levels of NOx and $O_3$ (İm et al. 2006).

Turkey is one of the countries where a large fraction of the population is exposed to harmful levels of air pollution. Metropolitan Istanbul is the most populated city of Turkey with a population exceeding 16 million. In this respect, many studies have been done on the air quality of İstanbul like Tayanç (2000), Elbir et al. (2010), Markakis et al. (2012), and Flores et al. (2020a). On the other hand, the largest province of Turkey, Konya, is one of the least studied regions in terms of air quality, and only a few studies can be found in the literature such as Dursun (2019), Kunt and Dursun (2016), and Polat and Durduran (2012). Furthermore, the population of Konya City has been increasing, leading to higher population density, an increasing number of vehicles, higher amounts of fossil fuel use for heating purposes, and growing demands for electricity. From the environmental viewpoint, one can say that higher consumption of fuels in and around the city is expected to increase emissions of pollutants and the frequency of air pollution episodes. On the other hand, with the guidance of clean air action plans (KCAAP 2019 and 2020), Konya Provincial Environmental Board meets several times a year and takes decisions based on the air quality regulations to control and reduce emissions (KPEB 2021). In this respect, we aim not only to study the recent air quality of Konya City but also to investigate the effects of the mitigation measures and control strategies applied by the authorities. We start by considering a high time-resolution data set of the criteria pollutants in the 2008–2018 period. Special emphasis was given to the quality of data and then we carried out data analyses, focused on the violation of limit values, and investigated relationships with meteorological factors. We gave special emphasis on any possible improvement in the air quality and considered the roles of actions taken by the authorities.

## Study area

Konya is the largest province of Turkey having a total surface land and lake areas of 40,838 km$^2$ and covers approximately 5% of the country's territory. The land surface area of the province is 38,873 km$^2$ and the majority of its territory is located in the high plains of Central Anatolia.

The average altitude of the province is 1016 m. Figure 1 shows the location of Konya in Turkey, topography, settlement maps, and population evolution of Konya. As it can be seen from the figure, Konya City is located on a plain surrounded by high hills on the western side and agricultural low lands on the east (Fig. 1b). Topography begins to rise up from the Meram district towards the west (i.e., Beyşehir Lake) generating peaks exceeding 1750 m. Figure 1c shows the five monitoring stations at Konya: Selçuklu, Selçuklu Belediye, Meram, Karatay Belediye, and Erenköy Belediye (Yeni Sille Belediye). As seen in this figure, the stations are mainly located in urban areas.

Konya province has the 7th place according to the ranking of population done in 2018 with respect to Address Based Population Registration System (Adrese Dayalı Nüfus Kayıt Sistemi-ADNKS) (Turkish Statistical Institute, 2018) with a population of 2,205,609 constituting 2.69% of Turkey's population. Population density is 56.74 people per km$^2$. Population of Selçuklu, Meram, and Karatay district centers within the boundaries of Konya Metropolitan Municipality constitute 54% of the population of Konya with a population of over one million. Figure 1d shows the population variability since 1927. An obvious increase in the population of Konya became stabilized in the 2000s. After the 1980s, county population decreased in favor of Konya City's population. This shows the evidence of immigration from rural to urban areas.

## Climate and emission sources

### Climate

Konya has a continental type Mediterranean climate with hot summers and cold winters. According to the Turkish State Meteorological Service (TSMS, 2021), the average temperature in July between 1929 and 2018 was 23.5 °C (Table 1) and the maximum temperature exceeded 30 °C during the summer months. The highest temperature recorded in Konya was 40.6 °C on July 30, 2000. During the winter, January's average temperature was below 0 °C and the average minimum temperature can sometimes be lower than − 4 °C. The lowest temperature recorded was − 28.2 °C on 6 January 1942. Due to Konya's high altitude and its dry summers, nightly temperatures in the summer months are cool. Precipitation levels are low with an average annual total of 322.4 mm and precipitation can be observed throughout the year. The wettest month is May and the driest is August with monthly totals as 43.5 mm and 4.9 mm, in order. The dominant wind direction is northerly, with north and north westerly wind constituting 58% of the cases.
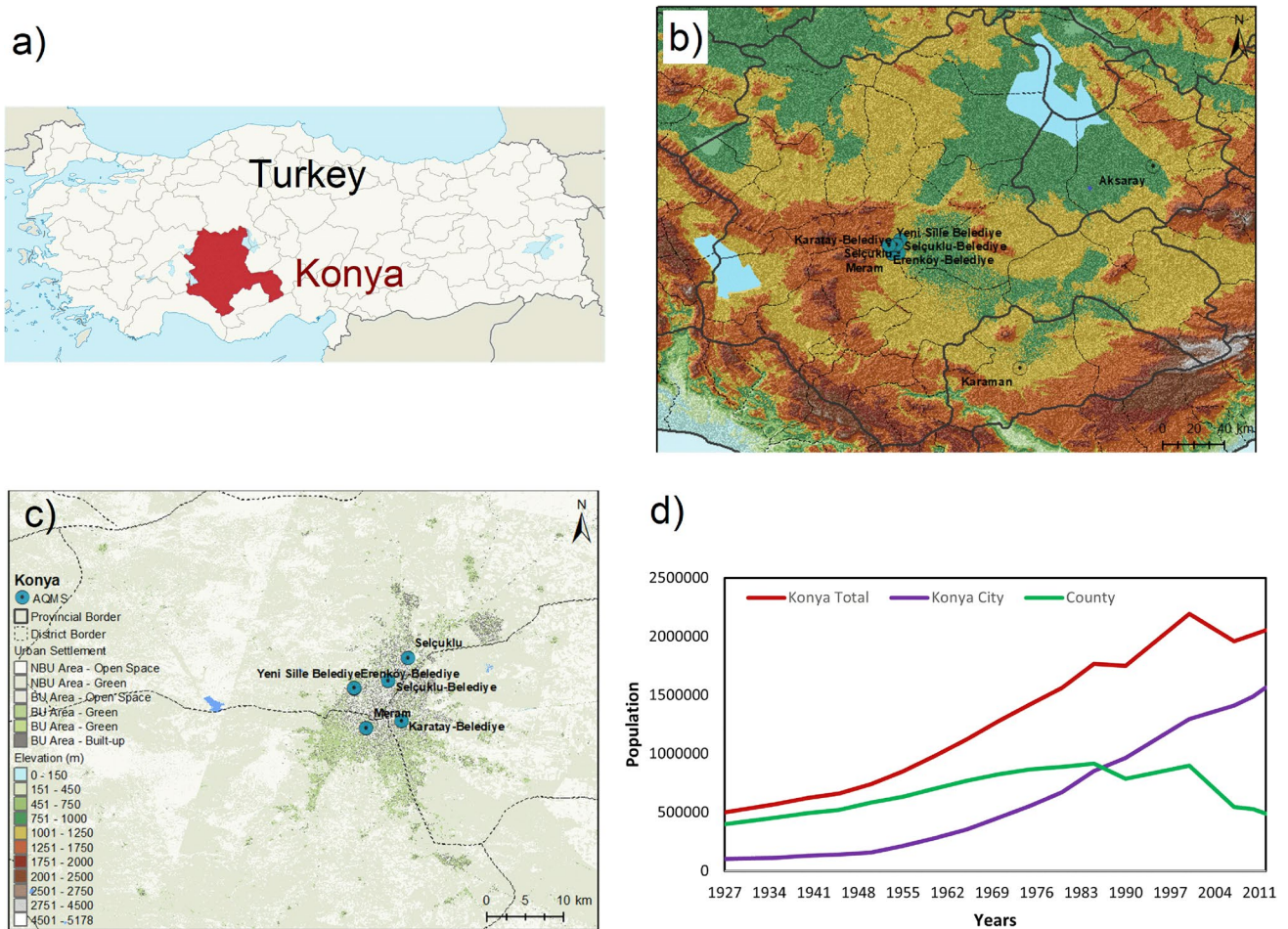
**Fig. 1** **a** Location of Konya in Turkey. **b** Konya geographical location and topography. **c** Settlement map with air quality monitoring stations (AQMS). **d** Population variability in the 1927–2012 period.

**Table 1** Climatological summary of Konya in the period 1929–2018

| | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec | Annual |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Avg. temp. (°C) | −0.2 | 1.4 | 5.6 | 11.1 | 15.8 | 20.1 | 23.5 | 23.2 | 18.5 | 12.5 | 6.3 | 1.7 | 11.6 |
| Avg. max. temp. (°C) | 4.6 | 7.0 | 11.8 | 17.5 | 22.3 | 26.6 | 30.1 | 30.2 | 26.0 | 20.0 | 13.0 | 6.6 | 18.0 |
| Avg. min. temp. (°C) | −4.2 | −3.3 | −0.2 | 4.3 | 8.6 | 12.6 | 15.8 | 15.6 | 10.9 | 5.9 | 0.8 | −2.4 | 5.4 |
| Mean daily sunshine hours | 3.3 | 4.7 | 5.9 | 7.1 | 8.9 | 10.6 | 11.6 | 11.2 | 9.5 | 7.2 | 5.3 | 3.2 | 88.5 |
| Mean prec. days | 9.9 | 8.4 | 8.8 | 9.0 | 10.6 | 6.6 | 2.2 | 1.5 | 3.1 | 6.1 | 6.6 | 10.0 | 82.8 |
| Avg. mon. tot. prec. (mm) | 37.6 | 28.5 | 28.9 | 31.9 | 43.6 | 25.5 | 6.3 | 4.6 | 12.3 | 30.0 | 32.0 | 42.1 | 323.3 |
| Record high temp. (°C) | 17.6 | 23.8 | 28.9 | 31.5 | 34.4 | 37.2 | 40.6 | 39.0 | 36.1 | 31.6 | 25.4 | 21.8 | 40.6 |
| Record low temp. (°C) | −28.2 | −26.5 | −16.4 | −8.6 | −1.2 | 1.8 | 6.0 | 5.3 | −3.0 | −8.4 | −20.0 | −26.0 | −28.2 |

## Air pollution emission sources in Konya

There are various industrial activities in Konya including the production of cement, sugar, machinery, chemicals, textile, food, packing material, electronic equipment, and paper. Industries are generally located in organized industrial zones mainly in the northern regions of the city as reported by the Konya Chamber of Industry (KCI 2022) and Konya Province Environmental Report (KPER 2019).

Within the boundaries of Konya province, there are 705 organizations with emission licenses (Kunt and Dursun, 2016). To our knowledge, there are 167 industrial organizations with high-pollutant qualifications in the city center, and the number of vehicles in traffic was counted as 593,089 in

the year 2014. Konya Clean Air Action Plan (2013–2019) (KCAAP 2019) declared that 88,899 out of 265,489 residential buildings are using natural gas for heating purposes in the city corresponding to 34% of the total and the remaining 176,590 buildings depend on coal. The abovementioned report expresses 3 main sources of air pollution in the city: residential heating, industrial emissions, and traffic. High levels of air pollution in a city not only depend on the emissions but also on topography and meteorology.

## Data collection and analysis

The principles of monitoring air quality according to EU norms are defined in the Air Quality Assessment and Management Regulation published in the Official Gazette dated as 06 June 2008 and numbered 26,898. Continuous air quality monitoring was performed by the Turkish Ministry of Environment and Urbanization as part of the national air pollution monitoring network. Data is publicly available and has been used in various research studies (Agacayak et al. 2015; Kabatas et al. 2014; Karaca et al. 2009; Flores et al. 2020b).

Air quality data of Konya province in the period of 2008–2018 was subjected to quality control, and the periods that have large missing data gaps or no data at all were not considered for the analysis. The periods with lack of data availability are shown as red bars in Figs. 2, 6, and 9. There are 5 active air pollution measurement stations in Konya that passed the quality check for the air pollution analyses: Selçuklu Belediye (37.9159 N, 32.5002 E), Karatay Belediye (37.8681 N, 32.5163 E), Erenköy Belediye (37.9066 N, 32.4600 E) (newly called as Yeni Sille Belediye), Selçuklu (37.9428 N, 32.5233 E), and Meram (37.8598 N, 32.4747 E). Generally, Selçuklu Belediye and Karatay Belediye stations have high quality data since the early 2016 (2015 for $PM_{10}$). Selçuklu and Meram have only $PM_{10}$ measurements and the reliable $PM_{10}$ data of these stations extends back to 2008. On the contrary, Erenköy Belediye has reliable observation data only in 2018. Periods belonging to the early phases of measurements had large percentages of missing data resulted in the elimination of those periods.
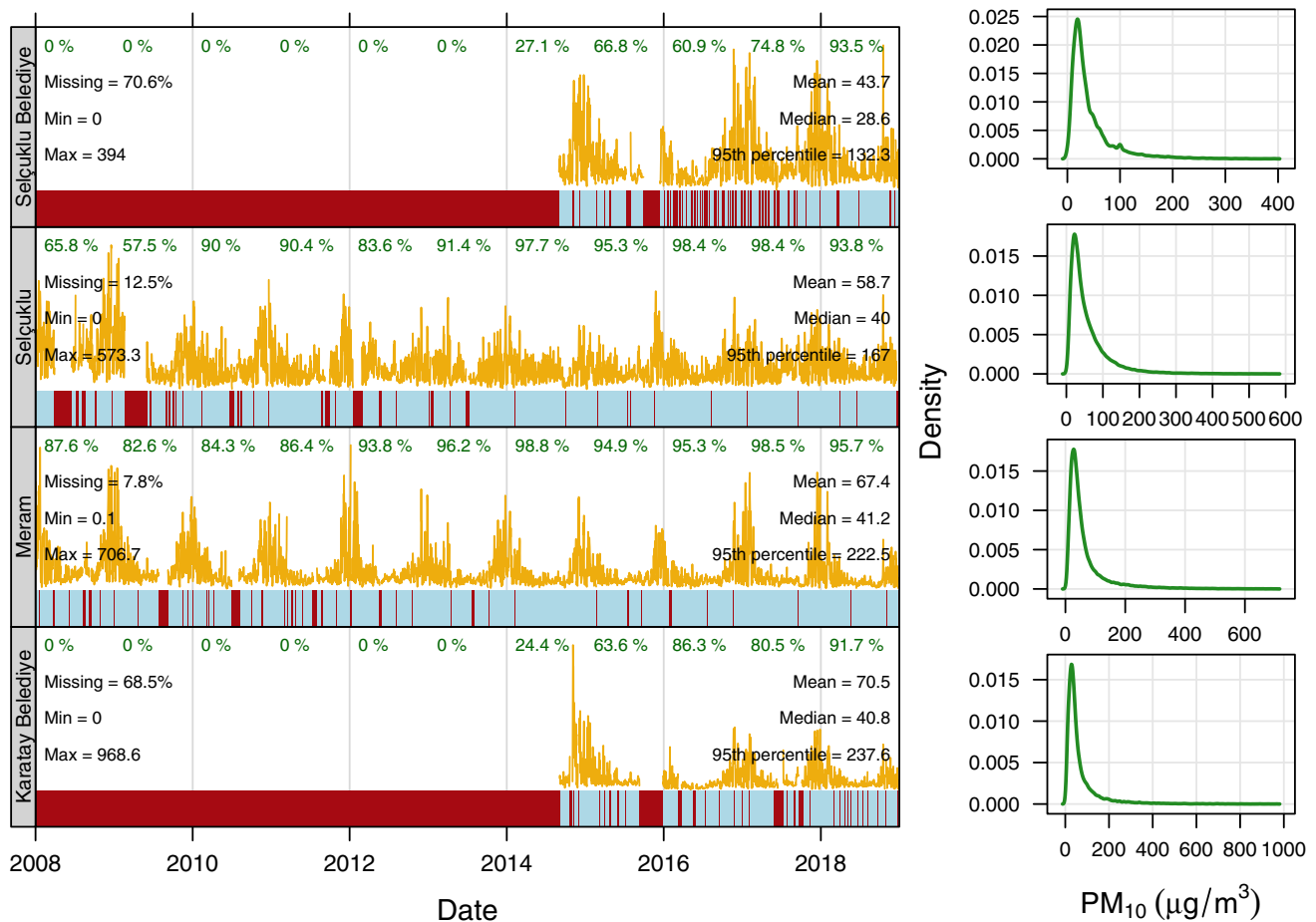


**Fig. 2** Hourly $PM_{10}$ statistics in Konya

# Results

Hourly monitored air quality data of CO, $NO_2$, $NO_x$, $PM_{10}$, $PM_{2.5}$, and $SO_2$ in the 2008–2018 period at five stations in Konya were subjected to various comprehensive analyses. We started by analyzing the maximum values and determining the exceedances with respect to the limit values.

## Violation of the limit values

Exceedance numbers were determined by considering all of the five stations of Konya and if a daily limit value of any pollutant is exceeded in any of the stations, then the limit value for that day in the city is considered to be exceeded. For the winter and annual cases, the concentration of each station was compared with each other and the maximum of them was considered. Table 2 provides the exceedance analysis for Konya between 2008 and 2018 and the values in red indicate violation of the standards. Except for winter and yearly, all values presented are the number of exceedances. Winter and yearly are given as average concentration values in $\mu g/m^3$. Values in red indicate the violation to the standards. Exc. column shows the numbers of excluded data after the quality check. According to the Air Quality Assessment and Management Regulation, the 8-h average of CO should not exceed 10 $mg/m^3$. No hourly limit value for CO is provided. The allowable limit values in short time periods are always larger than those having longer time periods. Because hourly CO concentrations in Konya did not exceed 10 $mg/m^3$ (Table 2), it can be reliably assumed that there is no violation of the CO limit value in any station of Konya.

According to the legislation, the 250 $\mu g/m^3$ hourly limit value of $NO_2$ should not be exceeded 18 times in a year to protect human health. $NO_2$ hourly limit was exceeded 494 and 456 h in 2017 and 2018, respectively, which are approximately 27 and 25 times greater than the 18 h yearly limit for $NO_2$. The yearly $NO_2$ limit (50 $\mu g/m^3$) was only exceeded in 2017 with an annual concentration of 83.6 $\mu g/m^3$.

In terms of $NO_x$, the yearly limit value of 30 $\mu g/m^3$ was violated in 2016, 2017, and 2018 with annual concentrations much greater than the limit of 130.1, 190.7, and 643.4 $\mu g/m^3$, in order. For $O_3$, the 8-h limit value of 120 $\mu g/m^3$ was exceeded seven times in 2016, four times in 2017, and again seven times in 2018.

$PM_{10}$ daily and yearly limits were exceeded throughout the measurement period with a large number of exceedances and very high concentrations. The number of days having concentrations higher than the limit is larger than 150 days in any given measurement year and up to 275 days in 2008. Associated with this, the annual concentrations have been higher than the 40 $\mu g/m^3$ limit value, with a maximum of 99 $\mu g/m^3$ in 2008. This is an indicator that Konya has serious $PM_{10}$ issues, especially during autumn and winter. Yuksel (2015) found $PM_{10}$ and $SO_2$ values to be climbing during autumn and winter in Ankara, the capital of Turkey. Konya and Ankara, both have similar geographic features; they are located on the Anatolian plateau and surrounded by high hills and mountains. Analysis of Yuksel (2015) revealed 50 $\mu g/m^3$ daily limit value of $PM_{10}$ was exceeded by 307 days during a year in Sihhiye and 263 days in Demetevler, two central stations of Ankara. These values have similarities with our findings in Konya in a way that the number of days violating the $PM_{10}$ limit value in Konya is always larger than 150 days in any given year and this value raises up to 275 days in 2008 (Table 1).

The hourly $SO_2$ concentrations did not exceed 350 $\mu g/m^3$ at any time. However, the yearly limit of $SO_2$, (i.e., 20 $\mu g/m^3$), was violated in 2011, 2012, and 2017 with values of 23.0, 20.3, and 26.3 $\mu g/m^3$, respectively. Wintertime violations are more pronounced, with violations in 2010, 2011,

**Table 2** Evaluation according to limit values. Cases where limit values are exceeded illustrated in bold. All values presented are the numbers of exceedances except for Winter and Yearly rows, where the values in those rows are provided as average concentrations in $\mu g/m^3$

| Pollutant | Period | Limit | Exc | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| CO | Max. daily 8 h | 10,000 | 1 | – | – | – | – | – | – | – | 0 | 0 | 0 | 0 |
| $NO_2$ | Hourly | 250 | 18 | – | – | – | – | – | – | – | 0 | 6 | **494** | **456** |
| | Yearly | 50 | 1 | – | – | – | – | – | – | – | – | 48.5 | **83.6** | – |
| NOx | Yearly | 30 | 1 | – | – | – | – | – | – | – | – | **130.1** | **190.7** | **643.4** |
| $O_3$ | Max. daily 8 h | 120 | 1 | – | – | – | – | – | – | – | 0 | **7** | **4** | **7** |
| $PM_{10}$ | Daily | 50 | 35 | **275** | **219** | **222** | **184** | **224** | **176** | **206** | **218** | **169** | **241** | **186** |
| | Yearly | 40 | 1 | **99** | **84.3** | **75.5** | **69.8** | **72.2** | **63.1** | **60.4** | **58.5** | **56.3** | **83.3** | **58.3** |
| $SO_2$ | Hourly | 350 | 24 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | Daily | 125 | 3 | 0 | 0 | 0 | **4** | 0 | 0 | 0 | 0 | 0 | **5** | 0 |
| | Yearly | 20 | 1 | 15.6 | 13.8 | 16.3 | **23** | **20.3** | 12.1 | 13.6 | 10.2 | 15.7 | **26.3** | 13.6 |
| | Winter | 20 | 1 | 16.7 | 14.8 | **25.1** | **36** | – | **25.9** | **21.3** | 13.2 | **39.8** | **30.1** | – |

2013, 2014, 2016, and 2017. The exceedances during 2011 and 2016 are almost twice the annual limit value of 36 and 39.8 μg/m³, in order. Orak and Ozdemir (2021) studied $PM_{10}$ and $SO_2$ concentrations in the 2015–2020 period for the 81 cities of Turkey, including Konya. The authors stated that the $SO_2$ concentrations are higher during the domestic heating season and after March, significant decreases can be observed. According to the results of this article, Konya's $SO_2$ average concentration was 13 μg/m³ during the period of 2015–2019 and decreased to 10 μg/m³ in 2020 with the effect of COVID-19 lockdown and restrictions. These values bear a close resemblance to our results of the annual $SO_2$ averages given in Table 2.

### $PM_{10}$ analysis

Five active $PM_{10}$ measurement stations exist in Konya: Selçuklu Belediye, Karatay Belediye, Erenköy Belediye, Selçuklu, and Meram. Selçuklu Belediye and Karatay Belediye stations have $PM_{10}$ data since the middle of 2014. On the contrary, Erenköy Belediye has measurements only in 2018; thus, it was not considered in the analysis. On the other hand, Selçuklu and Meram $PM_{10}$ data are relatively continuous through the 2008–2018 period. Figures 2, 3, 4, and 5 show the statistics, temporal variations, pair plots, and trends of the hourly $PM_{10}$ measurements in the Konya province. It can be seen from Fig. 2 that the highest mean values of $PM_{10}$ was 70.5 μg/m³ in Karatay Belediye followed by 67.4 μg/m³ in Meram, 58.7 μg/m³ in Selçuklu, and 43.7 μg/m³ in Selçuklu Belediye.

In the Turkish regulation, the 24-h limit of $PM_{10}$ is given as 50 μg/m³ for the protection of human health, and this limit

should not be exceeded more than 35 times in a year. One can see in Fig. 3 that the daily limit value is mainly violated during winter and autumn at all of the stations. Ninety-fifth percentile data belonging to the stations are 132.3, 167, 222.5, and 237.6 μg/m³, in order, given in Fig. 2. Karatay Belediye and Meram districts have the highest percentiles. It is obvious that 95th percentile values are much higher than the daily limit values. Density figures (Fig. 2) also show that the violation of the 50 μg/m³ limit value is very frequent. Thus, it should be expressed that $PM_{10}$ pollution is a serious problem during winter and autumn in the Konya province.

Seasonal plots (Fig. 3) of $PM_{10}$ illustrate that during winter and autumn days, very high concentrations of $PM_{10}$ exist in all of the locations, threatening human health. Karatay Belediye and Meram districts have the highest daily values; some exceeding 100 μg/m³ level in Karatay Belediye during certain days of the week. Diurnal variability is more pronounced than weekly variability. High values exist during the morning rush hours and during the night. Primary particles and secondary particles that form from the volatile chemicals in the atmosphere can be responsible for these high levels of $PM_{10}$ pollution. In all of the seasons and for all of the stations, a noticeable observation is the high nighttime and morning rush hours $PM_{10}$ levels. This condition is related with emissions, meteorology, and chemistry. Prevailing stable atmospheric conditions during the night generate stagnant and low wind speed conditions, particularly during winter. A result of this is the generation of low mixing heights trapping the pollutants close to the surface.

Pairs figure (Fig. 4) shows that $PM_{10}$ data highly obey the log-normal distribution. It can be stated that high positive correlations exist among the stations, and the highest
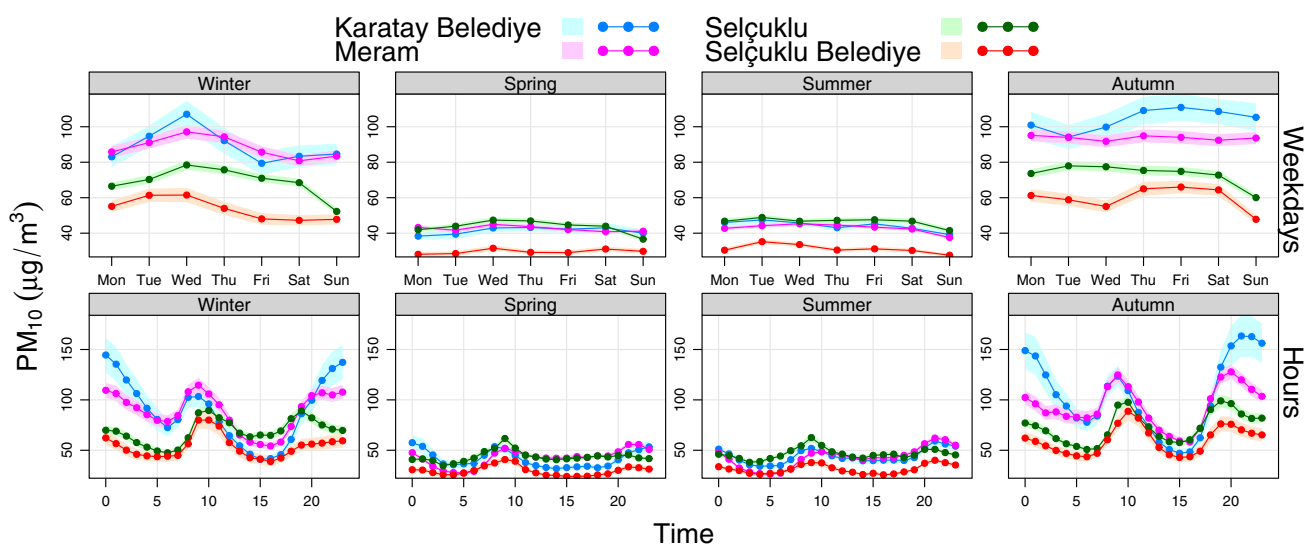


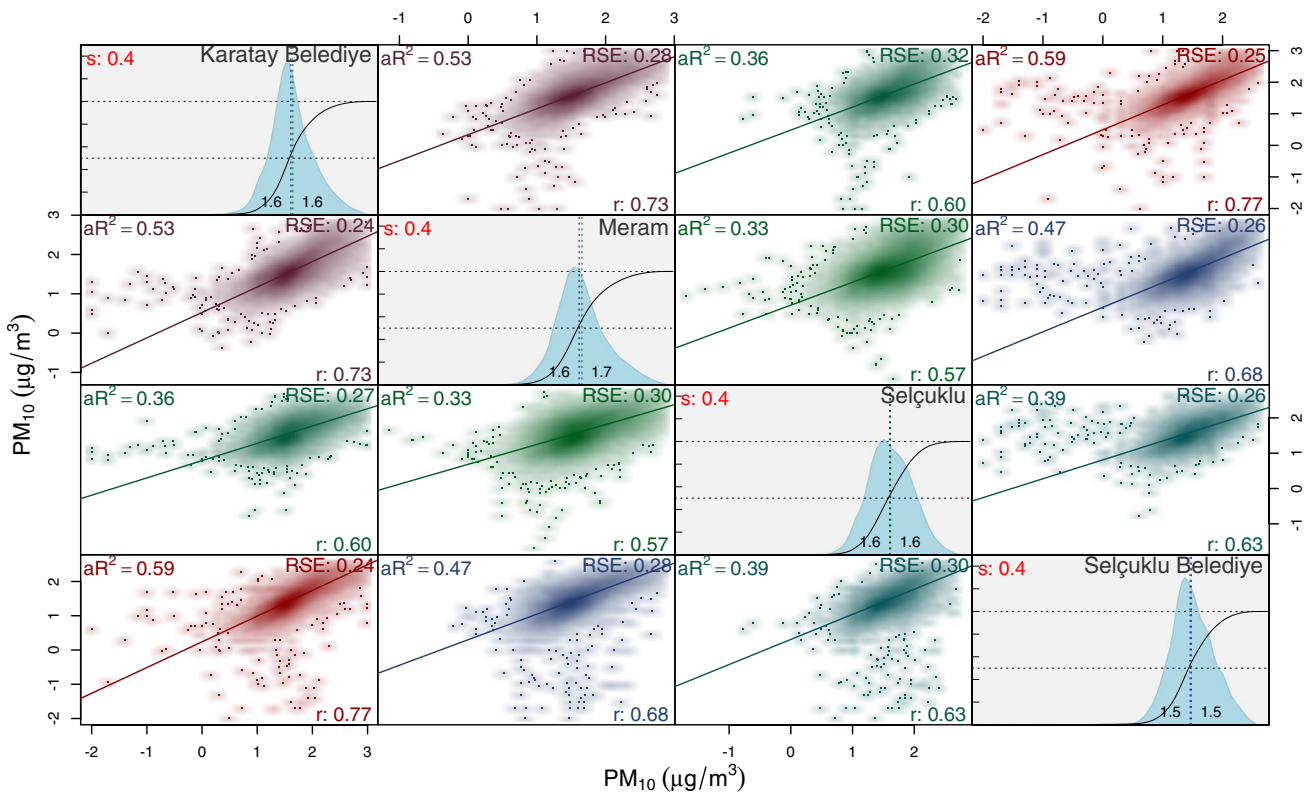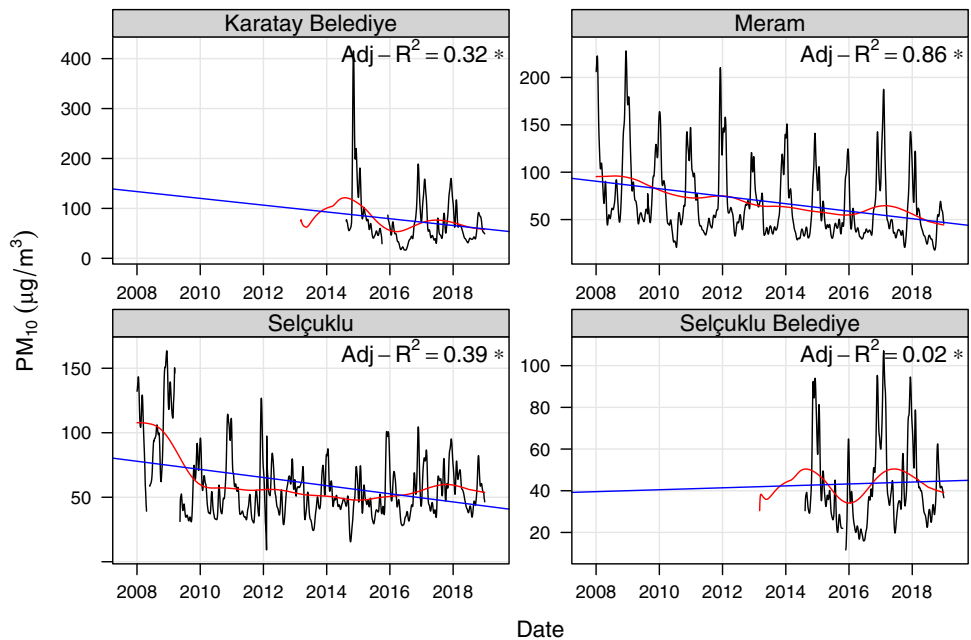**Fig. 3** $PM_{10}$ variabilities during the seasons. Daily variability in a week (top) and hourly variability in a day (bottom)

**Fig. 4** Hourly $PM_{10}$ pairs plots

**Fig. 5** Trends of $PM_{10}$ during the measurement period



correlation is between Selçuklu Belediye and Karatay Belediye with the Pearson correlation coefficient, $r = 0.77$ and adjusted $R^2 = 0.59$. These high correlations are indicators for similar emissions sources and atmospheric dynamics at all sampling stations in the Konya City.

Figure 5 shows the trend plots of the stations. Generally, long-term measurements show considerable decreasing trends in $PM_{10}$ levels with adjusted-$R^2$ values 0.86 for Meram and 0.39 for Selçuklu. This decrease in the concentrations with respect to the years can be a result of clean air

action plans and mitigation measures that have been applied in the province to reduce pollutant emissions. Konya Clean Air Action Plan (2013–2019) was in force until 2019 and nowadays Konya Clean Air Action Plan (2020–2024) is in force (KCAAP, 2019 and 2020).

Another agency dealing with the air quality of the city is Konya Provincial Environmental Board that meets several times in a year and takes decisions according to air quality regulations and clean air action plan to control and reduce emissions. Properties of fuels that are allowed to be stored, sold, and used in the city center of Konya (Karatay, Meram and Selçuklu Districts) were determined by the Konya Province Environmental Board (KPEB) in its April 2021—243 meeting. One of the decisions established limited values for the imported coal to be used in residential heating in dry basis as 0.8% sulfur, 28% fly ash as maximum levels, and 7250 kcal/kg heating value as a minimum value. Limit values applied for industrial use of coal is 1% sulfur, 36% fly ash as maximum levels, and 6500 kcal/kg heating value as minimum limit (KPEB, 2021).

Furthermore, a project co-funded by the European Union and the Republic of Turkey titled "Technical Assistance for Improving Air Quality and Raising Public Awareness in Cities in Turkey-CityAir (in line with CAFE Directive)" studied the air quality of Konya together with 30 provinces via developing emission inventories, doing air quality modeling studies, recommending mitigation measures, and raising public awareness. This project can help authorities update clean air action plans by providing up-to-date air quality data obtained from measurements, inventories, and modeling studies. The availability of long-term trends, such as

in the case of $PM_{10}$, is important for the evaluation of air pollution control technologies and potentially the need for the implementation of new strategies.

### $NO_x$ analysis

Violation of the limit values in Konya shows that the primary pollutant of interest is $PM_{10}$ and to a secondary importance level, $NO_x$ and $O_3$. Thus, in the scope of this article, we gave special emphasis on the analyses of these pollutants and the evaluation of the results via topography and meteorology. Three active air pollution measurement stations in Konya measure NO, $NO_2$, and $NO_x$: Selçuklu Belediye, Karatay Belediye, and Erenköy Belediye. Selçuklu Belediye and Karatay Belediye stations have high quality $NO_x$ data since the early 2016. On the other hand, Erenköy Belediye has reliable $NO_x$ data only in 2018; thus, it was not considered in the analysis. Figures 6, 7, and 8 show the statistics, time variations, and trends of the hourly $NO_x$ measurements in the Konya province. The highest mean values of $NO_x$ were 291.9 µg/$m^3$ in Selçuklu Belediye and 200.2 µg/$m^3$ in Karatay Belediye urban stations (Fig. 6). The high values of $NO_x$ in urban stations can be attributed to the intensity of photochemical activity over the city. The lowest mean concentration was observed in Erenköy Belediye, with a value of 40.3 µg/$m^3$.

According to Turkish regulation (i.e., Air Quality Assessment and Management Regulation), the annual limit of 30 µg/$m^3$ of $NO_x$ has been applied to protect human health. Since there is no hourly limit expressed in the legislation, comparisons of measurements with the limit value were not performed. Erenköy (Yeni Sille) Belediye is located
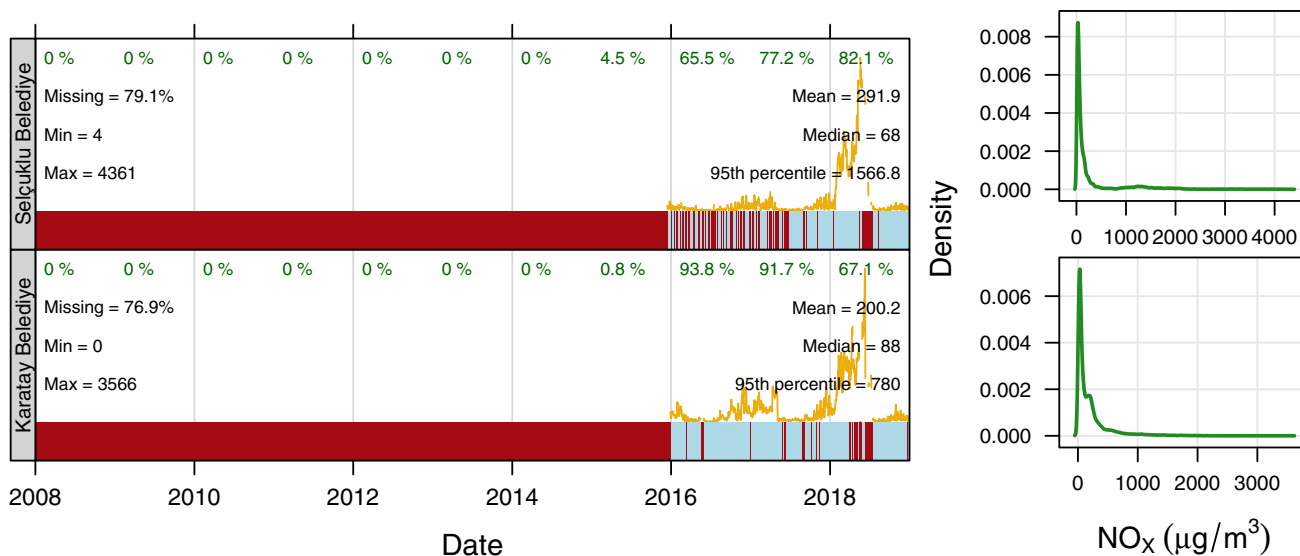
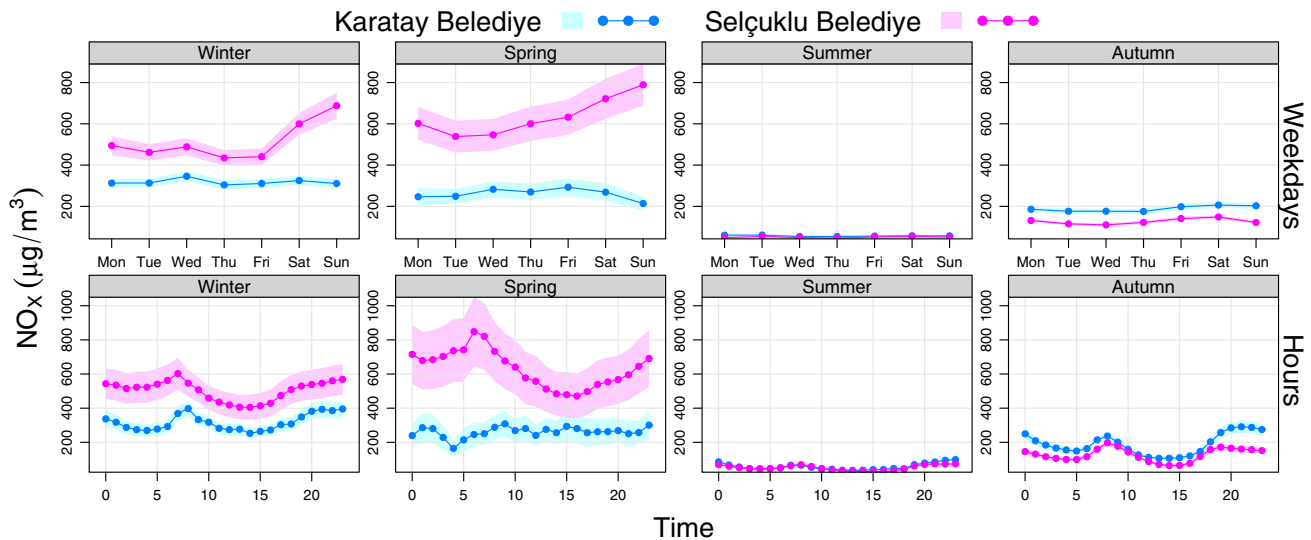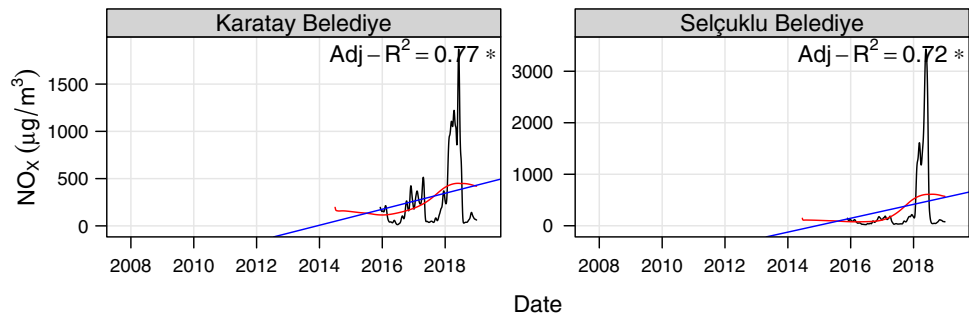

**Fig. 6** Hourly $NO_x$ statistics in Konya

**Fig. 7** Hourly NO$_x$ variability during daytime and daily NO$_x$ variability during the week belonging to each season

**Fig. 8** Trends of NO$_x$ during the measurement period



in a suburban region northwest of Konya City surrounded by parks and green areas. The dominant north and north-westerly winds at Konya turn this location into an upwind location that can be considered as a background site in the majority of the observed cases. A careful investigation of the density plots on the right-hand side of Fig. 6 shows that the annual limit value of 30 μg/m$^3$ was rarely exceeded in Konya. The 95th percentile data belonging to the stations are 1566.8 and 780 μg/m$^3$, in order, meaning that during 95% of the hourly cases, NO$_x$ concentrations were below those values.

Seasonal plots (Fig. 7) of NO$_x$ illustrate that winter and spring have high concentrations in the urban locations, Selçuklu Belediye and Karatay Belediye. It is intuitively clear in the plots that Selçuklu Belediye has the highest NO$_x$ concentrations during the winter and spring seasons, mainly influenced by the emissions from traffic and residential heating, and photochemical reactions may exacerbate the problem. For Selçuklu Belediye, during weekdays of winter, Monday, Tuesday, and Wednesday NO$_x$ averages are slightly higher than those of Thursday and Friday, as it is for CO, NO, and NO$_2$. Interestingly, during winter and spring,

when there are high concentrations of NO$_x$ at Selçuklu Belediye, weekend levels are found to be larger than those of weekdays. However, this condition cannot be seen at Karatay Belediye.

Morning rush hour peak NO$_x$ values generated mainly by traffic are clearly visible in Fig. 7. Emissions, photochemistry, and meteorology play an important role in the hourly variation of NO$_x$. Emissions during morning traffic act as precursors of photochemical reactions that produce O$_3$, aldehydes, and PANs. Thus, a sharp decrease in NO$_x$ levels after the rush hours during the morning is expected owing to photochemical reactions and dilution, especially during the spring and autumn seasons when solar radiation intensity is higher than in the winter. But photochemical activity does not exist during evening and night; thus, NO$_x$ levels remain high for long periods of time. A strong diurnal cycle caused by photochemical reactions is not observed in the summer. Although higher solar irradiance is expected in the summer, concentrations are much lower than those observed in winter and spring. This shows the importance of residential heating emissions in the production of photochemical smog during the cold season.

In all of the seasons and almost all of the stations, a prominent result is the high nighttime $NO_x$ levels. This condition is directly related with meteorology and chemistry. Prevailing stable atmospheric conditions during night generate stagnant and low wind speed conditions. A scientific result of this is the generation of low boundary layer or mixing heights, trapping the pollutants close to the surface. Low wind speeds or calm conditions exacerbate the problem by decreasing the pollutant transport in the horizontal leading to high $NO_x$ values. On the contrary, at noon and early afternoon, during sunny days, differential warming up of the surfaces by solar radiation generates an unstable atmosphere associated with higher boundary layer altitudes and moderate to strong mountain-valley breezes. This situation leads to the transport of pollutants in the horizontal as well as in the vertical generating considerably lower levels of pollution. Reactions of NO and $NO_2$ with the hydrocarbons is a quick process during the daytime producing photochemical pollutants. Therefore, these reactions can be responsible of the sharp decrease of $NO_x$ concentrations after 08:00 or 09:00 h.

Figure 8 shows that the urban stations of Konya have increasing $NO_x$ trends (i.e., blue line) with considerably large Adj-$R^2$ values of 0.77 for Karatay Belediye and 0.72 for Selçuklu Belediye. Since Erenköy Belediye has data available only for 2018, the trend established is not reliable and not included in the analysis. This feature of $NO_x$, together with those of NO and $NO_2$, should be taken into account because $NO_x$ is an important contributor of photochemical smog.

## $O_3$ analysis

Similar to $NO_x$ measurements, $O_3$ is also measured at 3 stations in Konya: Selçuklu Belediye, Karatay Belediye, and Erenköy Belediye. Selçuklu Belediye and Karatay Belediye stations have high quality $O_3$ data since the early 2016. On the other hand, Erenköy Belediye has $O_3$ measurement only in 2018; thus, it is generally outside the scope of the analysis. Figures 9, 10, and 11 show the statistics, time variations, and trend figures of the hourly $O_3$ measurements in the Konya province. As shown in Fig. 9, the highest mean values of $O_3$ are 34.6 µg/m$^3$ in Karatay Belediye and 27.1 µg/m$^3$ in Selçuklu Belediye urban stations. The lowest mean concentration belongs to Erenköy Belediye, with a value of 24.8 µg/m$^3$.

According to the Turkish regulation, 180 µg/m$^3$ 1-h average limit value is established as a *notice threshold* and 240 µg/m$^3$ 1-h average limit value is established as a *warning threshold*. The 95th percentile data belonging to the stations are 75, 87, and 65.9 µg/m$^3$, in order. Thus, it is obvious that 95th percentile values are much lower than the hourly limit values. Density figures (Fig. 9) also show that there is no violation of the 180 µg/m$^3$ limit value in any of the stations.

Figure 10 illustrates the daily (top) and hourly (bottom) variabilities of $O_3$ concentrations with respect to seasons for two main stations of Konya, Selçuklu Belediye and Karatay Belediye. It is obvious that $O_3$ values are much higher during spring and summer while daily averages exceed 50 µg/m$^3$ in Karatay Belediye. Selçuklu Belediye has lower values compared to the Karatay Belediye, and in spring, they decrease almost linearly during the days of the week from Monday
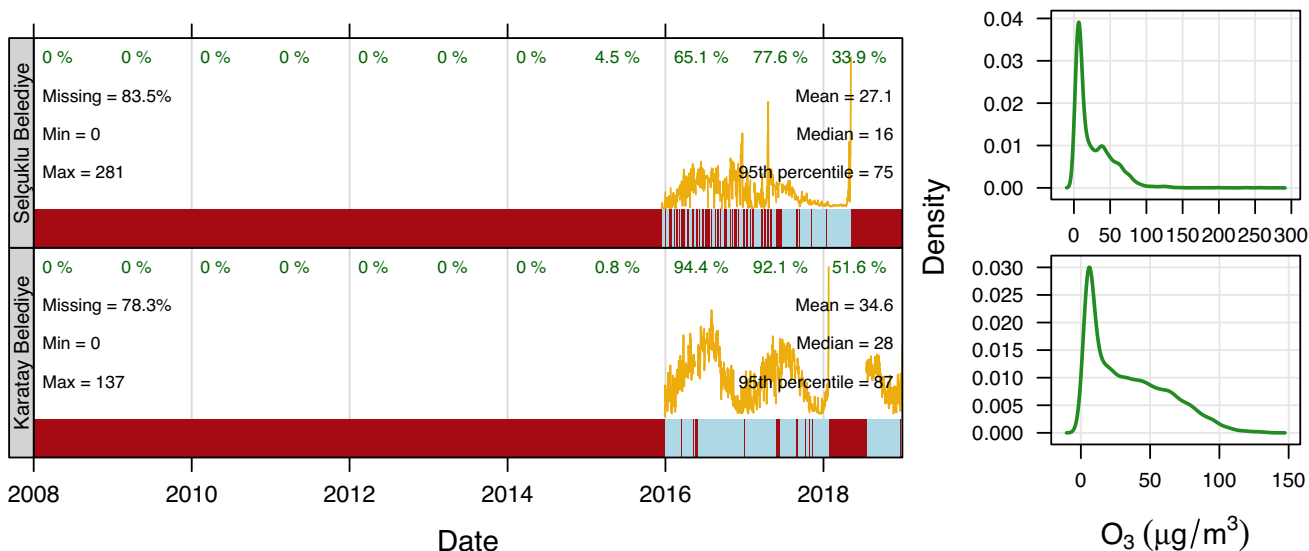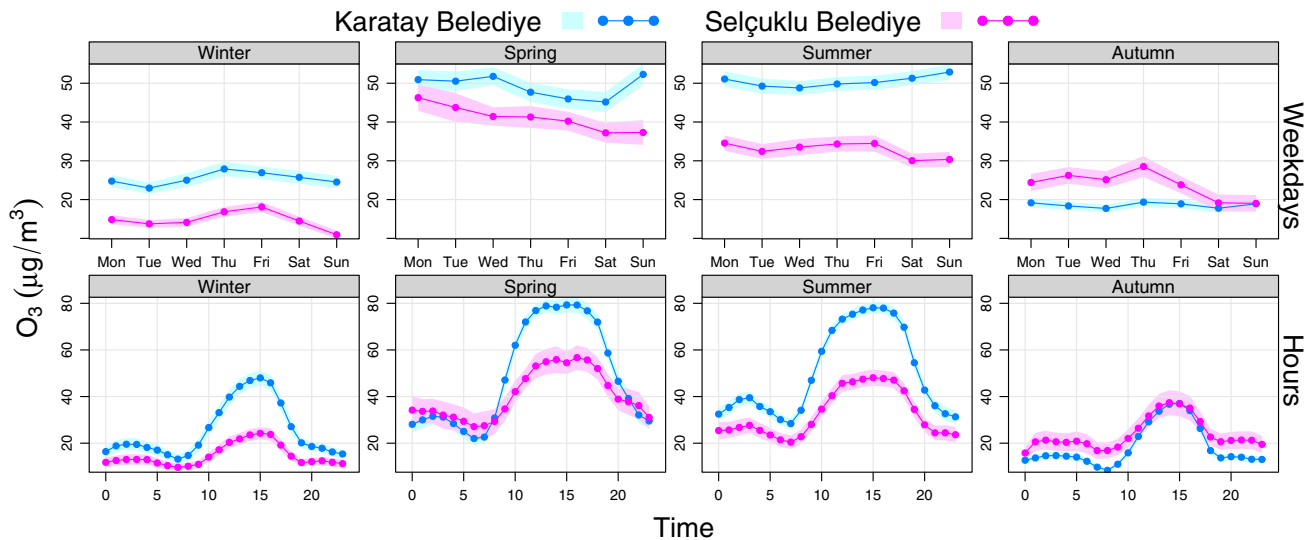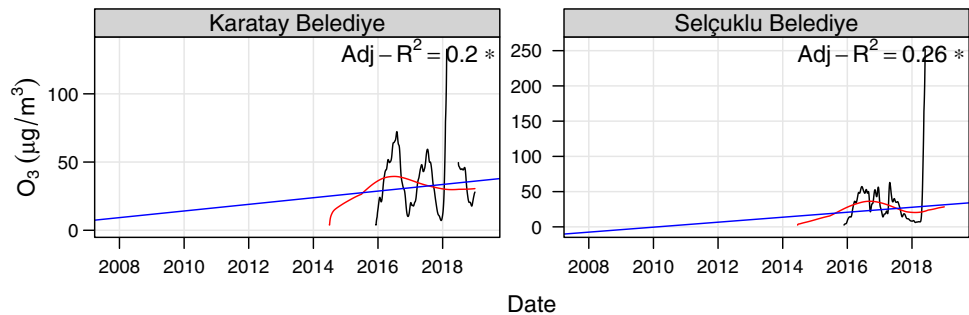


**Fig. 9** Hourly $O_3$ statistics in Konya

**Fig. 10** O$_3$ variabilities during the seasons. Daily variability in a week (top) and hourly variability in a day (bottom)

**Fig. 11** Trends of O$_3$ during the measurement period



to Sunday, starting from a level well above 40 μg/m$^3$ and dropping below that level towards the end of the week. In Selçuklu Belediye, the lowest values of O$_3$ can be seen during the weekends of all seasons. Though, this is not the case for Karatay Belediye with Sunday concentrations climbing to the peak in spring and summer. So, we can deduce that the variability of O$_3$ values during the days of the week is not well established in Konya.

Diurnal figures show that the maximum O$_3$ levels are always around noon or early afternoon, owing to the sequence of photochemical reactions. In Karatay Belediye, spring and summertime hourly average values climb up to 80 μg/m$^3$ around 15:00 h. Although Selçuklu Belediye O$_3$ curves have similar diurnal variability, the concentrations remain below 60 μg/m$^3$. Selçuklu Belediye is located in the north, and Karatay Belediye located further south, closer to the center of the city (Fig. 1c). The dominant wind direction over the city is northerly; thus, this can provide a reasonable explanation for the higher concentrations of O$_3$ in Karatay Belediye. O$_3$ is a secondary pollutant forming later in the photochemical reaction sequence and thus can be found at elevated concentrations over the further downwind regions,

corresponding to Karatay Belediye in this case. During northerly winds, Selçuklu Belediye resides in the upwind area, providing lower O$_3$ levels compared to those of Karatay Belediye. The presence of the secondary pollutant, O$_3$, in the region can be an indicator of the presence of other photochemical pollutants like aldehydes and PANs that may be hazardous.

Similar to NO$_x$, which are O$_3$ precursors, the urban stations of Konya have increasing O$_3$ trends, with Adj-$R^2$ values 0.26 for Selçuklu Belediye and 0.2 for Karatay Belediye (Fig. 11). This feature of O$_3$, together with those of NO, NO$_2$, and NO$_x$ should be taken into account because violation of the limit values can occur in the near future.

## Case study: episodic analysis

The period of January 29–February 5, 2018 was characterized as having PM$_{10}$ concentrations much higher than the daily limit value of 50 μg/m$^3$ and was chosen for the episodic analysis. PM$_{10}$ variability during the various sampling stations is illustrated in Fig. 12a. The average of Selçuklu Belediye, Karatay Belediye, and Meram stations is depicted
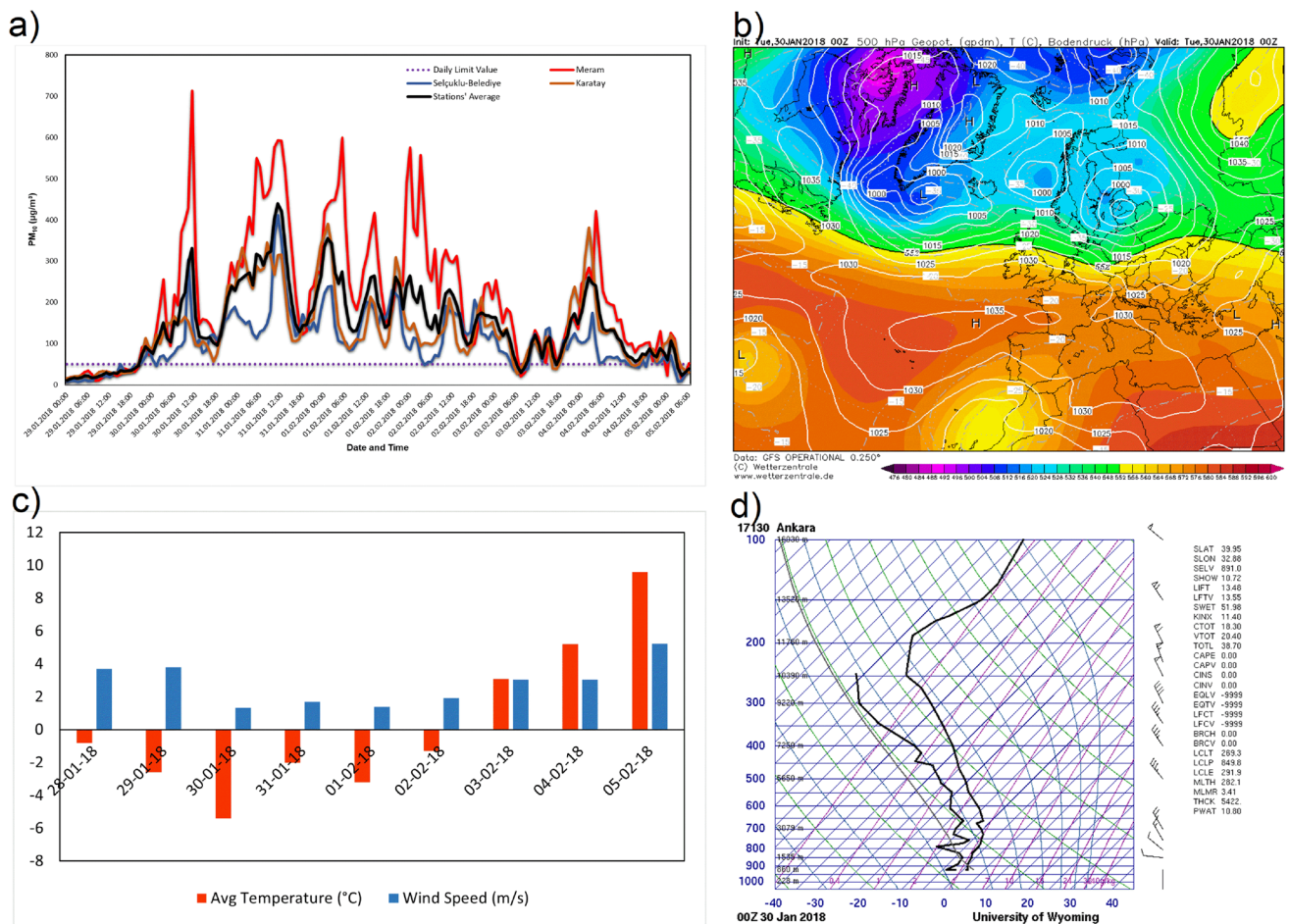
**Fig. 12** **a** PM$_{10}$ variability during January 29, 2018–February 05, 2018 episode. **b** Surface SLP and geopotential height at 500 mb level, credit: wetterzentrale.de. **c** Daily average temperature and wind speed. **d** Skew-T diagram obtained from radiosonde at Ankara, credit: University of Wyoming.

with a black line (i.e., stations' average). Episode PM$_{10}$ data of Erenköy Belediye and Selçuklu were missing so these stations are not included in the analysis. During this 1-week episode, PM$_{10}$ concentrations exceeded 500 μg/m$^3$ several times in Meram station and reached a peak value of 707 μg/m$^3$ on January 30, 2018. Other stations and the average of the stations also showed a similar variability to Meram during the episode. Pearson correlations among the stations showed a high relationship with $R$ values of 0.64 between Meram and Selçuklu Belediye, 0.67 between Meram and Karatay Belediye, and 0.72 between Selçuklu Belediye and Karatay Belediye. $R$ values raised above 0.8 when we considered correlations among the station data and the stations' average as $R$ to be 0.93 between Meram and the stations' average, 0.83 between Selçuklu Belediye and the stations' average, and 0.87 between Karatay Belediye and the stations' average.

In order to study this episode in terms of meteorology, atmospheric transportation mechanisms in the vertical and

horizontal are considered. Reanalysis of sea level pressure (SLP) together with 500-mb geopotential height map on January 30, 2018 00Z was generated and is presented in Fig. 12b. White contours show sea level isobars. Middle Anatolia was under the effect of a strong high pressure system with SLP greater than 1030 mb. Isobars are located far away from each other, generating low-pressure gradient force and in turn low wind speeds or calm conditions. Figure 12c shows the daily average temperature and wind speeds. Daily average temperature was lower than 0 °C during the episode until February 3, 2018. The temperature decreased steadily to a lowest average of 5.4 °C on the 30th of January. This is a clear indicator of the demand of fossil fuel, mainly Turkish lignite having high amounts of sulfur and ash with low heating value for residential heating.

Additionally, the daily average wind speed remained below 2 m/s during a 4-day period from January 30 to February 2. Figure 12d provides the atmospheric sounding obtained for Ankara station (WMO no: 17130) at 00Z on

January 30, 2018. The vertical temperature profile is the dark solid curve on the right (Fig. 12d). It is clear that the temperature increases with height from the surface to an approximate altitude of 3 km, showing the presence of a strong persistent inversion, trapping the emitted pollutants at the surface. This typical atmospheric condition together with the hollow-like topography of the region and high local emission rates from residential heating generated significantly high $PM_{10}$ levels.

Studies done for İstanbul and Erzurum established the importance of meteorology and topography on air quality. Kasparoglu et al. (2018) studied $O_3$, NO, and $NO_2$ concentrations in İstanbul and emphasized that anticyclonic pressure systems and low winds can lead to $O_3$ accumulation at the surface boundary layer. They also expressed that $O_3$ precursors can be transported over long distances, and $O_3$ formation is supplied far from the sources by the meteorological conditions, especially by the prevailing winds. Yilmaz et al. (2021) studied the air quality of Erzurum, a cold continental climate city in Turkey, via urban microclimatic and morphologic properties. They observed that the polluted air accumulates in the pits and areas having high building density, and the air pollutant concentrations

are low in high altitudes, sloping areas, and in the wind-effective open areas.

In order to find whether this episode was a result of long-range transport of pollutants, we generated HYSPLIT backward simulations ending at Konya 00:00 UTC on Jan 30, 2018 for three elevations: 10, 50, and 80 m above ground level (Fig. 13). Lagrangian backward trajectories show that in a 24-h time period, the motion of air masses at the three elevations is similar and the air masses generally circulate around the city. Additionally, one can see from the bottom part of the Fig. 13a that there is no rise in the trajectories. This is the evidence that the air quality deteriorated in the city mainly by local emissions and critical meteorological conditions and not by the transport from regional or long-range sources.

## Conclusions

The availability of long-term air pollution trends, such as the case of $PM_{10}$, is important for the evaluation of the existing air pollution control strategies and for determining the need for the potential development and implementation of new policies. For this reason, hourly monitored air
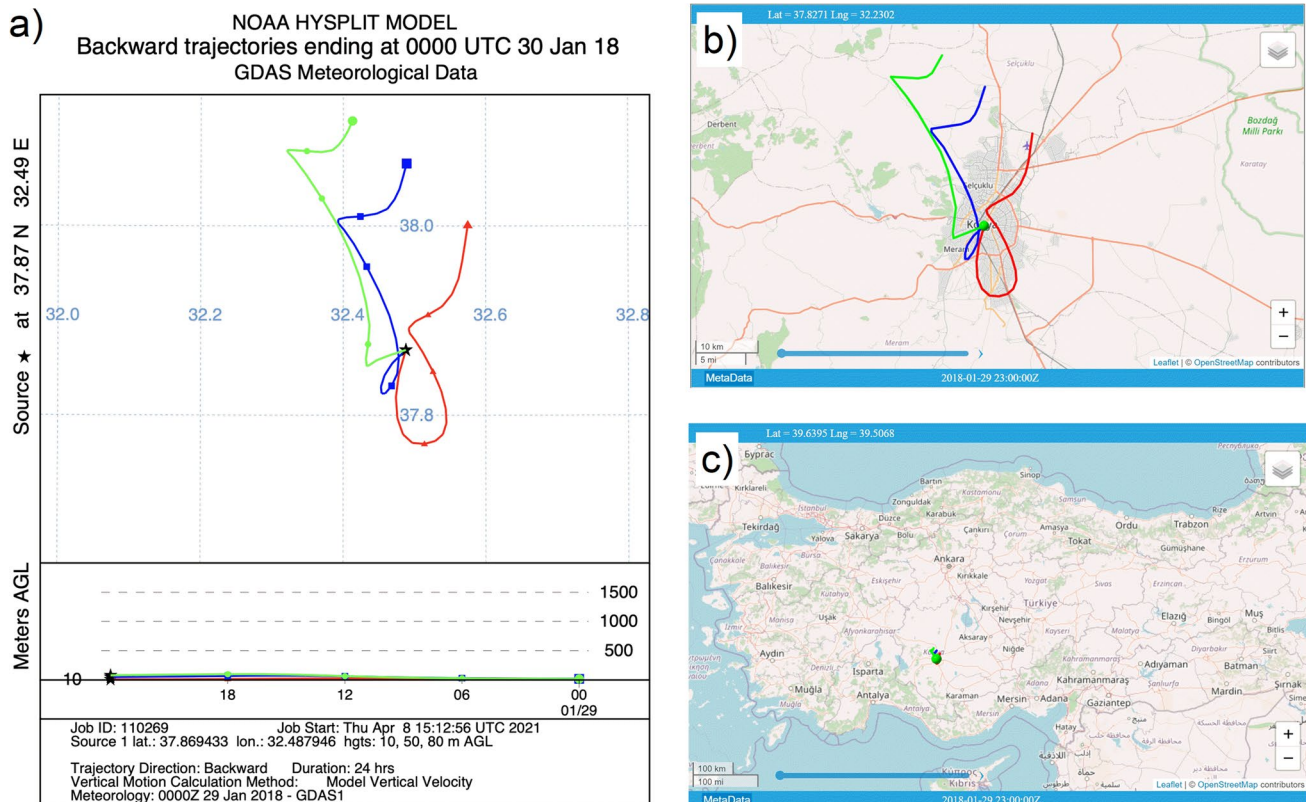


**Fig. 13** 24-h HYSPLIT backward trajectories ending at 00:00 UTC Jan 30, 2018 for three heights: 10, 50, 80 m. **a** Trajectories on coordinate gridlines. **b** Trajectories shown on Konya and **c** Trajectories shown on Turkey.

quality data of CO, NO, $NO_2$, $NO_x$, $PM_{10}$, $PM_{2.5}$, and $SO_2$ for five stations of Konya was subjected to temporal and spatial variability analyses in the 2008–2018 period. It was found that the worst problem was caused by $PM_{10}$ pollution, where $PM_{10}$ daily and yearly limits were exceeded throughout the measurement period with very high number of exceedances and concentrations. The number of days having concentrations higher than the limit is larger than 150 days in any given measurement year, climbing up to 275 days in 2008. The seasonal analysis of $PM_{10}$ measured in Konya illustrated very high concentrations of particulates during the winter and autumn days, especially in Karatay Belediye and Meram districts.

The study revealed that the violation of the limit values generally occurs during winter days having low temperatures with high fossil fuel combustion for residential heating and industrial purposes. Natural gas is available in the city, but coal is much cheaper than gas; this generates a challenge as lignite has been continuously used, especially by people with limited resources for domestic heating. So, the use of Turkish lignite having high sulfur and ash content with low heating value can be given as the main culprit of having low air quality during the cold seasons.

To exacerbate the problem, winter season is most prominent in having strong high pressure systems. These type of weather systems are generally associated with low wind speeds and radiation inversions generating critical times in terms of air quality. Frequent air pollution episodes can be encountered in the city during these critical times of the heating season (November–March). On the contrary, during noon and early afternoon of the sunny days (a typical characteristic of high pressure systems), differential warming-up of the surfaces by sun generates unstable atmosphere associated with higher boundary layer altitudes and moderate to strong mountain-valley breezes in the Konya area transporting the pollutants in the horizontal as well as in the vertical generating considerably higher air qualities.

A case study done for the January 29, 2018–February 05, 2018 period showed the importance of meteorology on the high levels of pollution. It was shown that during this period, Konya province was under the effect of a strong high pressure system together with cold weather leading to daily mean temperatures lower than 0 °C, the majority of the time. This increased the demand for fossil fuel combustion for domestic heating. Additionally, low winds and strong inversions generated stagnant atmospheric conditions that further worsened the air quality. In brief, we can say that local emission sources like industries, traffic and residential heating, plus critical weather conditions limiting the transport and dilution of chemicals, and the location of the city among high hills and its urban morphology limiting the ventilation can generate frequent air pollution episodes in Konya.

Long-term analysis of pollutants showed the existence of decreasing trends in $PM_{10}$ levels, slight increases in $O_3$, and more prominent increases in $NO_x$ levels. The decrease in particulate matter levels can be attributed to the clean air action plans and mitigation measures applied in the province to reduce pollutant emissions. In one of the recent attempts, Konya Provincial Directorate of Environment established limit values on the quality of fuels allowed to be used in the province. For the imported coal, maximum limits of 0.8% sulfur, 28% fly ash, and minimum 7250 kcal/kg heating values were established in 2021. While for the industrial use of coal, 2021 decisions required the maximum thresholds to be 1% sulfur, 36% fly ash, and minimum 6500 kcal/kg heating value. We can expect to see the results of these decisions on the air quality of Konya in the near future. The most effective mitigation measure aiming to increase the air quality of Konya can be given as the reduction in emissions of primary pollutants and the precursors of the secondary pollutants. With the increasing population of the city, strict measures should be developed and applied to control and reduce the emissions of the chemicals. The fact "strength comes from unity" can be considered by the authorities, and Konya Provincial Directorate of Environment can think about working together with other leading institutions/organizations in the province like Konya Metropolitan Municipality and Chamber of Industry to tackle the Konya's air quality problems and develop and implement new strategies in the near future.

As a future work, high-resolution emission inventory can be developed for the Konya region, and this inventory could be used to do a precise and sophisticated chemistry-based air quality modeling study to assess the spatio-temporal variability of air pollution, evaluate the effects of urban morphology on the air quality, and better understand the mechanisms of secondary pollutant formation.

## Declarations

**Ethics approval and consent to participate** Not applicable.

**Consent for publication** Not applicable.

**Competing interests** The authors declare no competing interests.

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