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Air quality improvement and its relation to mobility during COVID-19 lockdown in Marmara Region, Turkey

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Abstract The outbreak of the novel coronavirus SARS-CoV-2 (hereafter COVID-19) has changed the daily routines of people around the world. When the first case was confirmed on 11 March 2020 in Turkey, the number of cases reached 4500 per day by 10 April in Turkey. Afterwards, the government declared more restrictive lockdown measures for 31 metropolitan cities starting 10 April, and it was implemented for the following weekends, national, and religious holidays. The change in concentrations of PM_{10}, $PM_{2.5}$, and NO_2 during these measures with respect to the pre-lockdown period, the same period in the previous years and for different levels of measures for the cities in the Marmara Region of Turkey was investigated in this study. The daily mean concentrations of PM_{10}, $PM_{2.5}$, and NO_2 obtained from 11 stations operated by the Ministry of Environment and Urbanization and Google mobility data are used in this study. Average $PM_{2.5}$ and NO_2 concentrations during the lockdown period declined with respect to the pre-lockdown period and the previous year for all stations. Average PM_{10} concentrations during the lockdown of 8 of 11 stations declined, while the rest of the stations increased with respect to the pre-lockdown period. In 9 of the 11 stations, the average concentration of PM_{10} decreased compared to the previous four years. In 7 of the 11 stations, the number of days exceeding WHO limit for PM_{10} was decreased during the lockdown period with respect to the pre-lockdown period. For $PM_{2.5}$, the number of days exceeding WHO limit was decreased during the lockdown period compared to the pre-lockdown period for all the stations. For NO_2, the number of days exceeding WHO limit was decreased during the lockdown period compared to the pre-lockdown period for 7 of the 8 stations. There is a significant relationship between mobility decrease and NO_2 concentrations in large cities. The correlation coefficients are generally lower in small cities in the study region.

Keywords COVID-19 · Air pollution · Turkey · Marmara Region

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Introduction

On the 11th of March 2020, the World Health Organization declared the SARS-CoV-2 (hereinafter COVID-19) as a pandemic, and on the same day the first positive case was detected in Turkey. The first partial lockdowns on weekend days in late March and April in some major cities were declared by the government. In addition, 3 and 4-day lockdowns including national holidays with social distancing have been implemented to prevent spreading the coronavirus. Across the country, intercity travel has been restricted from 27 March. However, despite these measures, the number of cases reached 4500 per day until the 10th of April. As of August 30, 2020, a cumulative total of 25 million confirmed cases and around 800,000 deaths have been reported globally since the start of the outbreak (WHO, 2020). All these restrictions have shut down industries and business sectors, drastically reduced motor vehicle traffic, and had a huge impact on people's social activities. Hence, the measures led to a decrease in air pollution emissions.

Numerous studies have reported on improvements in air quality due to the effects of COVID-19 based on partial and total lockdown measures (e.g., Baldasano, 2020; Collivignarelli et al., 2020; Nakada & Urban, 2020; Tobias et al., 2020; Siciliano et al., 2020; Sicard et al., 2020; Şahin, 2020; Dantas et al., 2020; Li & Tartarini, 2020; Xu et al., 2020; Wetchayont, 2021; Hashim et al., 2021). Xu et al. (2020) indicated that the effects of the COVID-19 outbreak presented significant reductions in the concentrations of $PM_{2.5}$, PM_{10}, SO_2, CO, and NO_2 in China. Similar behaviors and reductions were also found in some Southeast Asian cities such as Bangkok, Kuala Lumpur, Singapore, and Manila. For example, Wetchayont (2021) presented a significant decreasing trend during the COVID-19-outbreak year based on the periods before lockdown, lockdown and after lockdown periods for the concentrations of $PM_{2.5}$, PM_{10}, O_3, and CO in Bangkok. Besides, Siciliano et al. (2020) discussed the impact of the partial lockdown on the ozone levels in the city of Rio de Janeiro, Brazil. A similar study has been conducted by Baldasano (2020) for Barcelona and Madrid during lockdown measures. He studied NO_2 values of Barcelona and Madrid during lockdown measures and found that the NO_2 concentration was significantly reduced by 50% and 62%, respectively. Additionally, Tobias et al. (2020) showed that quarantine measures led to an improvement in air quality in Barcelona.

Significant results were also found in several European cities such as Barcelona, Istanbul, Madrid, Milan, and Munich. In addition, Şahin (2020) found significant decreases during March 2020 in Istanbul. For example, she reported reductions in PM_{10} (32–43%), $PM_{2.5}$ (19–47%), NO_2 (29–44%), CO (40–58%), and SO_2 (34–69%), respectively.

Meanwhile, several studies have used the mobility data to better understand the relationship between air pollution measurements and mobility during the COVID 19 measures (Li & Tartarini, 2020; Wang et al., 2020; Zhu et al., 2020). Li and Tartarini (2020) declared that trends of $PM_{2.5}$ and NO_2 were significantly correlated with mobility data for Singapore. Wang et al. (2020) investigated the effect of population mobility and airborne particulate matter on the spread of COVID-19 in several cities in China and concluded that the risk of COVID-19 transmission may be associated with mobility and airborne particulate matter. In addition, Zhu et al. (2020) studied the mediating effect of air pollution on the association of human mobility and spread of COVID-19. They concluded the unit increase in human mobility index is associated with an increase of 6.45% of the daily confirmed cases with the mediating effect of air quality index of 19.47%.

Marmara region which is located in the northwest of Turkey (Fig. 1) is the major economic region in Turkey in terms of industry, trade, tourism, and agriculture. About 25 million people live in eleven cities in this region. Table 1 presents the air quality stations and their characteristics.

Air pollution for the Marmara Region and in particular for Istanbul was investigated from different perspectives. Unal et al. (2011) investigated the influence of meteorological factors on spatial and temporal variations of PM_{10} concentrations in Istanbul. Kasparoglu et al. (2018) investigated the spatial and temporal variations of O_3 and NO_x concentrations at 7 rural and 15 urban sites in the Marmara Region of Turkey. They showed that the results indicate that surface O_3 is an extensive problem throughout the Marmara Region. Im et al. (2010) studied the PM_{10} episode in Istanbul using couple weather research and forecast model and air quality model. They conclude that, the new inventory used for Istanbul improved the PM_{10} assessment results compared to the previous model studies. Çapraz et al. (2016) investigated the association between air pollution and mortality in Istanbul for the period of 2007–2012. They found that mortality from cardiovascular disease, respiratory diseases, and total non-accidental causes in İstanbul are related to air pollution.

The COVID-19 lockdown's impact on air quality in the Marmara region is currently unknown except partly in Istanbul. Therefore, this study aims to assess the variations of air quality concentrations from the 11 stations and evaluate their associations with mobility trends during the COVID-19 partly lockdown measures by using statistical analysis.

The outbreak of the novel coronavirus COVID-19 has changed the daily routines for the lives of people

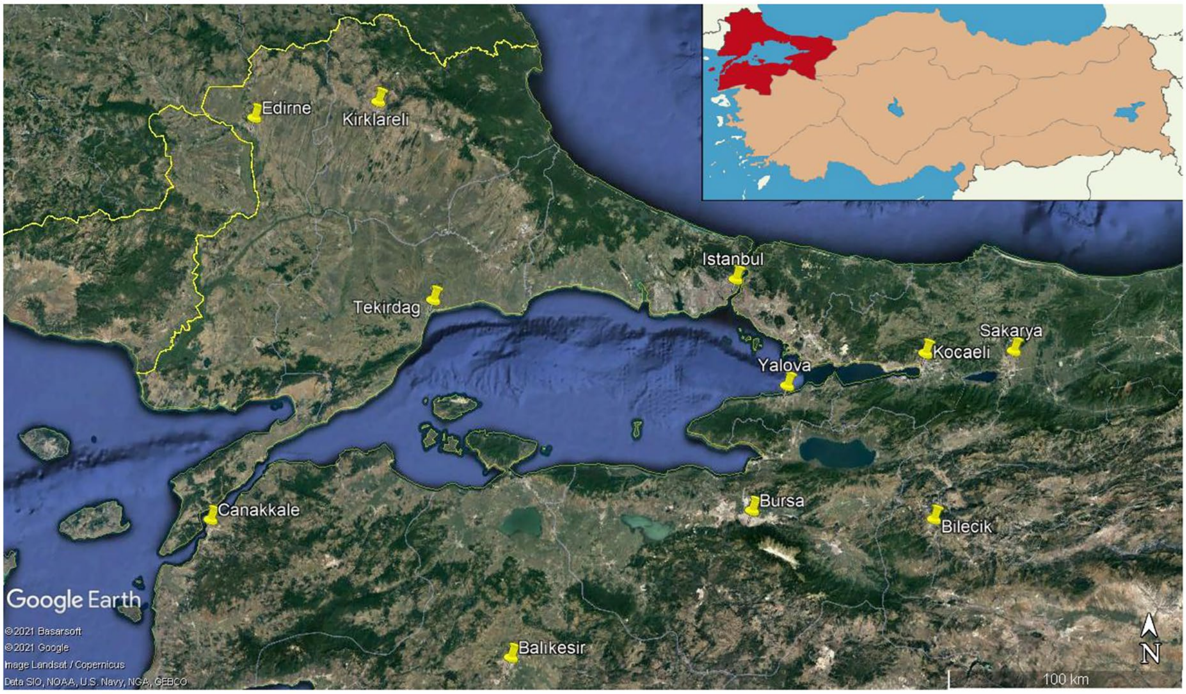

Fig. 1 The Marmara Region and location of air quality monitoring stations (Google Earth, 2021 & Wikipedia, 2021)

all over the world. The first case of the virus appeared in Wuhan, China, which is well known as one of the world's biggest trade and transportation centers, in December 2019. The virus has spread worldwide in a short period of time and the World Health Organization (WHO) has declared it as a global pandemic by 11 March 2020 (WHO, 2020). Most of the world's national governments took action by introducing strict rules to control the spread of the virus after they confirmed the first cases in their countries.

As a precaution, international flights to China, Iran, and Italy which were already experiencing strong

Table 1 Description of the urban air quality stations in the Marmara Region used in this study

Station	PM_{10}	$PM_{2.5}$	NO_2	Distance to residential areas (m)	Distance to industrial areas (km)	Distance to major roads (km)
Balıkesir	2016–2020	2019–2020	2019–2020	126	2.7	0.82
Bilecik	2016–2020	2019–2020	-	25	3.3	0.17
Bursa	2016–2020	-	2019–2020	425	0.5	0.64
Çanakkale	2016–2020	2019–2020	2019–2020	25	7.1	1.09
Edirne	2016–2020	2019–2020	2019–2020	35	5.2	0.16
İstanbul	2016–2020	2019–2020	2019–2020	120	5.7	0.01
Kırklareli	2016–2020	2019–2020	2019–2020	76	1.3	0.1
Kocaeli	2016–2020	2019–2020	2019–2020	252	3.6	0.32
Sakarya	2016–2020	2019–2020	-	30	0.8	2.34
Tekirdağ	2016–2020	2019–2020	-	25	0.8	1.15
Yalova	2016–2020	2019–2020	2019–2020	140	12.7	2.01

increases in confirmed cases, were canceled before the first case was diagnosed in Turkey. After the first case was confirmed in Turkey on 11 March 2020, the authorities first closed the airway transportation, then the borders to most of EU and neighbor countries. The primary, secondary and post-secondary schools stopped teaching in-class by 17 March, and they switched to online teaching. Indoor and outdoor gatherings were postponed or canceled as well as restaurants, cafes, and gyms closing by 20 March. Later, there were several actions undertaken such as closing non-essential businesses, stay-at-home orders, applying social distance measures and lockdown measures. Nationwide, intercity travels were limited by 27 March. However, in spite of these measures, the number of cases reached 4500 per day by 10 April. Afterwards, the government declared more restrictive lockdown measures for 31 metropolitan cities starting 10 April, and it was implemented for the following weekends, national and religious holidays. These full lockdown measures were removed by 1 June (Wikipedia, 2020). All these restrictions changed people's daily life routines and directly affected the daily commute. Therefore, it could be expected that the level of air pollution in these cities were lower with the COVID-19 lockdown measures.

The impact of COVID-19 on local air pollution has already been investigated. Several research groups have published recently about the change in ambient pollutant concentrations in major cities around the world (Adams, 2020; Baldasano, 2020; Lian et al., 2020; Menut et al., 2020; Otmani et al., 2020; Zangari et al., 2020). Adams (2020) investigated the air pollution in Ontario, Canada during COVID-19 and stated that NO_2, NO_x, and O_3 decreased during study period, while $PM_{2.5}$ did not change.

A study was published recently for Istanbul as well (Şahin, 2020). Although studies conducted on changes in local concentrations have shown a link between air pollution and impact of the restrictions imposed by COVID-19, early studies also indicate that ambient concentrations may be affected in a regional and global scale. For example, the study conducted by Menut et al. (2020) for Western Europe concludes that lockdown measures caused a decline in PM and NO_2 concentrations due to low traffic volume. Another research article (Rodriguez-Urrego and Rodriguez-Urrego, 2020) showed that $PM_{2.5}$ concentrations in 50 densely populated cities around the world have been reduced by 12%. Besides, a more comprehensive study (Venter et al., 2020) also found evidence of COVID-19's impact on tropospheric and ground level concentrations. They demonstrated the reduction of NO_2 and $PM_{2.5}$ while a marginal increase in O_3 concentrations was noted, and they also identified a relationship between these changes in concentrations and traffic volume. Additionally, Chu et al. (2020) investigates the behaviour of $PM_{2.5}$ and NO_2 pollution in China, and they found a reduction in $PM_{2.5}$ levels of 35% for China (Hubei excluded) with less significant decreases in SO_2 and CO. As expected, they also report that there was an increase in O_3 concentration. Lastly, a study was conducted by Shehzad et al. (2020) using satellite and monitoring data for India, and this study showed a significant decrease in NO2 concentrations. Almost all studies suggest a very important degree for the decline in pollutant concentrations for different locations around the world.

In this study, the link between the COVID-19 lockdown measures and their impact on the ambient air quality concentrations in the Marmara region of Turkey was examined. There are 11 cities in the region, 6 of which have a population of more than 1 million. Also, this region is well-known for its industrial zones. In addition, some previous studies have examined air pollution in the region (Kahya et al., 2017; Kasparoglu et al., 2018) previously. However, we use traffic-related monitoring sites and focus more on the change in traffic-related background concentrations.

This study is based on regional basis analysis and contributed to the latest literature on air pollution during the COVID-19 pandemic. Additionally, we compare concentrations during the periods in which lockdown measures were implemented and compare these to the same periods during non-pandemic years. This study also includes Google's mobility data which helps to explain the results quantitatively. The presented study is different than that by Şahin (2020). This study considers the pre-lock down period from the 1st of January to the 17th of March, while it was a limited period in the period of 1–15 March. The study area covers the Marmara Region while in that study, only Istanbul was taken into consideration. Şahin (2020) compares the mean values of pollutant concentrations in only two periods, before lockdown and after lockdown. In this study, the average concentrations during the lockdown were evaluated relative to other periods as well as pre-lockdown. Furthermore, this study considers the mobility data in order to find a link between the mobility values and the average concentrations.

This paper is organized as follows: the study area, air pollution data and methodology are described in "Data and methodology". The results are presented in "Results and discussion," and the main conclusions are drawn in "Conclusion".

Data and methodology

Study area

The Marmara Region is located in the northwestern part of Turkey and contains the 11 cities studied here. The Sea of Marmara is the inland waters of the region, and seven of these cities are located on the shore of the Sea of Marmara. In addition, five cities (Istanbul, Tekirdağ, Kırklareli, Kocaeli, and Sakarya) are situated on the coast of the Black Sea, and three (Çanakkale, Balıkesir, Edirne) have a coastal zone on the Aegean Sea (Fig. 1). The region has an area of about 68,000 km^2 with a complex terrain, and this area corresponds to 8.5% of Turkey's total area.

Marmara Region is selected as the study area because of its large number of population, important amount of industrial production, and its busy railways. According to the address-based population registration system, the Marmara region has a total population of 25,731,357. That means 30% of Turkey's population lives in this region. Istanbul, one of the megacities in the world with a population of more than 15 million is also located in this region (TUIK, 2021a). The Marmara region is responsible for 48% of the industrial production developed in Turkey, and there is a diverse array of industries operating in the region (Demirarslan & Akıncı, 2018). There are 7,445,695 motor vehicles in the region, accounting for 31% of total number of motor vehicles in Turkey. The number of cars is 4,561,594, and it is one-third of the total cars in Turkey. Gasoline-powered cars are 24.4% of the total cars and those of diesel are 38.3%, which means there are about 1.1 million gasoline-powered cars and 1.75 million diesel-powered cars. (TUIK, 2021b).

Air quality data

Major air pollutants including PM_{10}, $PM_{2.5}$, and NO_2 measured by the Marmara Clean Air Center (MCAC) (10 stations) and Greater Istanbul Municipality (1 station) used in the study were shown in Table 1. All the stations are urban air quality stations, and their distance to industrial areas changes between 0.8 and 12.7 km. The distance of the stations to the major roads vary between 10 and 2.34 km. The PM_{10} data are available for the period 2016–2020 at all stations. The $PM_{2.5}$ data are available for the 2019–2020 period at 10 stations, while NO_2 is available for only eight stations during the same period. Beta-ray absorption method is used in PM analyzer and measures between 0 and 10.000 µg/m^3. PM measurement devices (Environnement SA MP101M, Thermo 5014i, Metone Bam 1020, Environnement SA PM162M, MCZ LVS16, LECKEL SEQ 47/50, and MCV HVS1) are being operated compatibly with EN 12,341 for PM_{10} and EN 14,907 for $PM_{2.5}$. The measurements of NO_2 are made using a Teledyne API-M200E nitrogen oxide analyzer by using chemiluminescence method and has a measurement range of 0–200 ppm. Certificated calibration gasses were used to calibrate gas analysis devices regularly. Data validation is conducted routinely by the Marmara Clean Air Center and Greater Istanbul Municipality. Additionally, all the data were checked to get irregular measurements, like zero and negative values. This data is widely used by researchers (Kasparoglu et al., 2018; Şahin, 2020, Çapraz et al., 2016). PM_{10} emissions on traffic originate from diesel vehicles rather than the gasoline-powered ones. Besides, most of the trucks, such as buses and commercial vehicles in transport and construction sectors, are powered by the diesel system (Unal et al., 2011). The $PM_{2.5}$ data are available for the 2019–2020 period at 10 stations, while NO_2 is available for only eight stations during the same period. Main sources of $PM_{2.5}$ are car and truck exhausts, industry, smoke from fires and residential heating. NO_2 is mostly emitted by combustion sources, e.g., car engines, residential heating, power plants, industries, and biomass burning. The number of the days exceeding the limit values of each pollutant according to World Health Organization (WHO, 2018) is also calculated. The annual average of the pollutants for each station is also calculated, and the level of 2020 is compared to the previous available years. According to WHO guideline limits of PM_{10}, $PM_{2.5}$, and NO_2 for 24 h are 45 µg/m^3, 15 µg/m^3, and 25 µg/m^3, respectively. The annual limits for PM_{10}, $PM_{2.5}$, and NO_2 are 15 µg/m^3, 5 µg/m^3, and 10 µg/m^3, respectively.

Some periods were chosen to make the comparisons of the pollutant concentrations. The first period is defined as the pre-lockdown period (hereafter PLD) covering the period from 1 January–17 March 2020. The second period is called the lockdown measures period (hereafter LDM) covering the dates from 18 March–1 June 2020. The third period is the post (or after) lockdown period (hereafter ALD) covering the period from 1 June to 31 August 2020. The change for the concentrations of PM_{10}, $PM_{2.5}$, and NO_2 were analyzed for three different steps. For the first step, the change of concentrations during LDM and ALD with respect to the PLD is investigated. This step may not provide valuable results due to seasonal effects because average concentrations of all the pollutants in this study decrease from winter to summer. In addition, the number of the days exceeding the WHO limits during the LDM period is compared to the number of days exceeding the WHO limits during the PLD period.

For the second step, the LDM period was divided into two parts; the first one covers the dates that full lockdown measures were applied for metropolitan cities (hereafter FLD), and the second covers the remaining FLD days (hereafter RFLD). The change in concentrations of air pollutants during FLD with respect to the RFLD days is then investigated.

In the third step, the change of the mean PM_{10} concentration during the LDM with respect to the mean PM_{10} concentrations for the same period during the previous 4 years. This step also investigates the change for the mean $PM_{2.5}$ and NO_2 concentrations during the LDM with respect to the same quantities of the same period of the previous year (2019). The $PM_{2.5}$ and NO_2 observations are compared to the previous year only due to data availability.

In the fourth step, the mean PM_{10} concentration is compared to the mean PM_{10} concentrations of the previous 4 years. This step also investigates the change for the mean $PM_{2.5}$ and NO_2 concentrations during 2020 with respect to the mean $PM_{2.5}$ and NO_2 concentrations of 2019. The $PM_{2.5}$ and NO_2 observations are compared to the previous year only due to data availability.

Mobility data

In this part of the study, datasets from Google were used to analyze how changes in mobility affected the air quality. In addition to the Google dataset, Apple dataset for driving was used in the Marmara region, which is only available for Istanbul and Bursa cities.

The mobility data provided by Google (2020) for public health officials are used in this study to understand the observed reduction in traffic. The mobility data is explained in six different categories as introduced by Google (2020). These categories are retail and recreation percent change, grocery and pharmacy percent change, park percent change, transit station percent change, workplace percent change, and residential percent change. Workplace mobility data are used to represent the traffic change, since people use many kinds of vehicles to go to work. The mobility data are represented as the percent change from a base line in the six categories. The baseline is the median value of mobility data covering the 5-week period from 3 January–6 February 2020.

Apple provides mobility data which is classified into only two categories: driving and walking. The data depends on the navigation query change done by Apple users in a day with respect to the navigation queries done in January 13, 2020. Navigation queries for driving provided by Apple are used in this study as mobility data. Apple data is available for only Istanbul and Bursa cities. Real traffic data of a location (41.06415 N, 28.99841 E) located close to the Istanbul air quality station is obtained from Greater Istanbul Municipality (2020) to get more insight about traffic reduction.

In this study, mobility data is used to show a relative trend of how people movements changed within the region each day as in Li and Tartarini (2020). Mobility data is highly correlated not only with air quality but also with the spread of COVID-19. Yilmazkuday (2021) concluded that, his study shows less mobility is associated with a decrease in COVID-19 cases and deaths. He used Google mobility data of 130 countries for the period of February 15 and May 2, 2020. Therefore, mobility has been included to our study. The relationship between mobility change and decline in air pollution levels are analyzed by Pearson's correlation coefficient. More details on Pearson's correlation coefficient should be found in Benesty et al. (2009) and references therein. All the figures were illustrated via the ggplot2 R-package (Wickham, 2016). All the calculations are done using R-programming (R Core Team, 2018; Wickham et al., 2018).

Results and discussion

PM_{10} concentration

Daily PM_{10} concentrations from the PLD during LDM and ALD are shown as time series located on the outer part of Fig. 2. The blue arrows indicate the decline of LDM and ALD with respect to PLD, while red arrows indicate increment. As seen in Fig. 2, most of the cities experience a decline of PM_{10} concentrations during both the LDM and ALD periods, while Yalova and Çanakkale demonstrate an increase during both periods. Besides, the Tekirdağ station shows an increase during the LDM period and a decrease during the ALD period, while the Edirne station shows the opposite changes. The colored big map of the region in the center of Fig. 2 describes the change in mean PM_{10} concentration during the LDM with respect to the mean PM_{10} concentrations during the same period from the previous 4 years.

The rate of decrease for the mean PM_{10} concentrations at all stations during the LDM with respect to PLD fluctuates between 14 (Kocaeli) and 30 (Bursa) percent except for the Çanakkale, Tekirdağ, and Yalova stations (Table 2; Fig. 2). The average for the region is decreased by 13%. The PM_{10} concentrations increased at Çanakkale, Tekirdağ, and Yalova by 3, 22, and 6%, respectively. The cause of this increase is two PM_{10} episodes created by the dust transport from western Turkey. All the stations that were in the inner band of the Marmara Region experienced the first episode, but the concentration levels are different. The second one is experienced by all the stations used in this study. Thus, all the stations experienced PM_{10} episodes at different levels, but the mean PM_{10} concentrations for each of the stations with lower background pollution levels increased. Western Turkey experiences Sharan dust transport during the whole year as supported by observations (Baltaci, 2017; Kabatas et al., 2018) and model

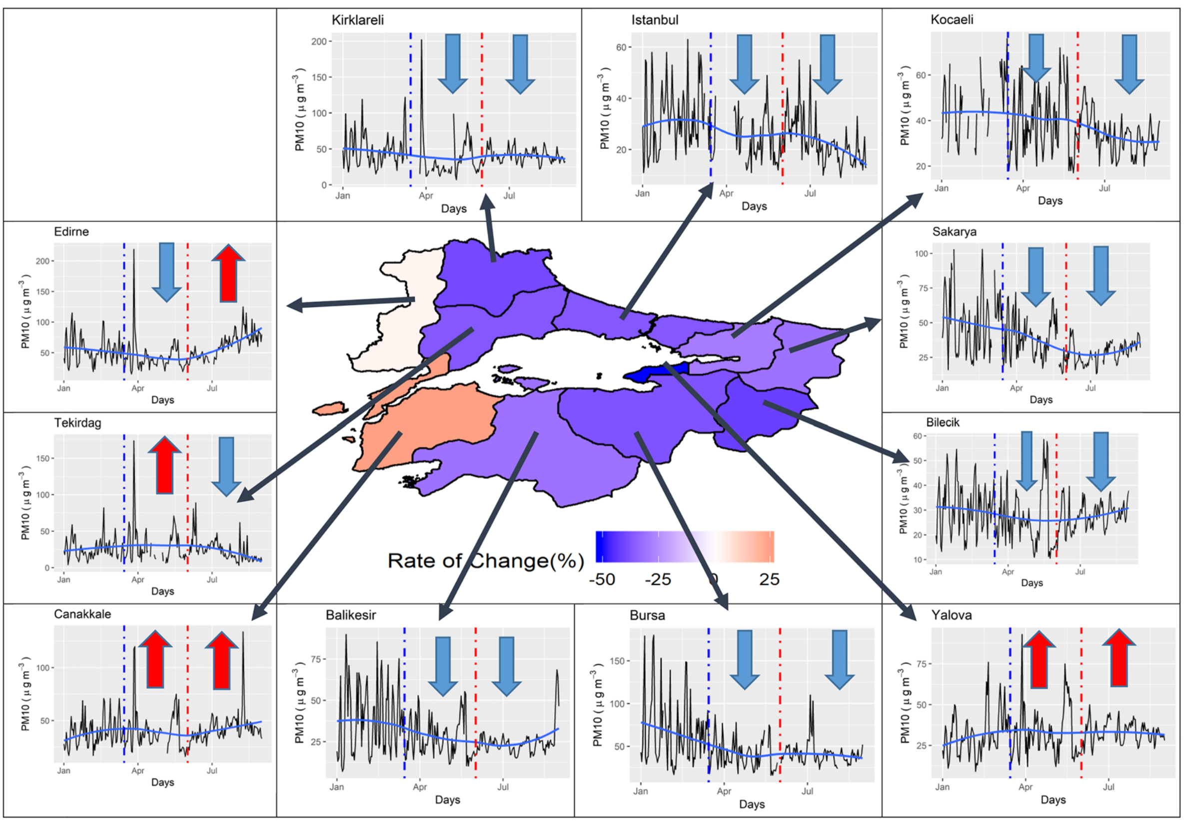

Fig. 2 (**a**) Outer time series represent the daily mean PM_{10} concentrations for the period of January 1–August 31, 2020. (**b**) Inner map represents the change of mean the PM_{10} concentration during LDM with respect to the mean PM_{10} concentrations of the same period of the previous 4 years

Table 2 Average PM_{10} concentrations during PLD, LDM, ALD periods, and the change of PM_{10} concentrations during LDM and ALD with respect to PLD

	Average (PLD) (µg/m^3)	Average (LDM) (µg/m^3)	Rate of change (%)	Average (ALD) (µg/m^3)	Rate of change (%)
Balıkesir	37.7	26.7	−29	24.2	−35
Bilecik	30.3	25.7	−15	27.2	−10
Bursa	66.7	40.6	−30	40.9	−30
Çanakkale	38.6	40.1	+3	42.6	+10
Edirne	54.1	43.1	−20	62.2	+15
İstanbul	31.8	23.9	−25	23.0	−27
Kırklareli	48.1	36.4	−24	40.5	−15
Kocaeli	45.8	39.3	−14	33.4	−27
Sakarya	49.9	37.5	−24	28.6	−42
Tekirdağ	25.4	31.3	+22	23.3	−8
Yalova	31.3	32.9	+6	33.0	+6

(Agacayak et al., 2015; Kabatas et al., 2018) studies. Otmani et al. (2020) found a decrease in PM_{10} measurements of 75% for Sale City located in NW Morocco, and Lian et al. (2020) found an average decline about 15% for the cities in Hubei Province. The previous one considers only one station, while the latter considers 12 stations. Our results are consistent with these studies.

The rate of change kept decreasing during the ALD as seen in Fig. 2 and Table 2 in the range of 8 (Tekirdağ) and 42 (Sakarya) percent except for Çanakkale, Edirne, and Yalova. The average for the region is decreased by15%. These three stations experienced increases in PM10 concentrations by 10, 15, and 6%, respectively. The only cause of the increase at Çanakkale is the PM_{10} episode. In Edirne, the mean PM_{10} levels increased by the PM_{10} episode and also by the background levels of PM_{10}. The increase in Yalova is created by only an increase in background levels. The main source of PM_{10} is domestic heating in large cities. However, in small cities the main contributor may be different. So, the behavior of PM_{10} in small cities such as Çanakkale, Edirne, and Yalova may vary due to emission sources.

The exceedance numbers of PM_{10} limits during PLD and LDM are seen in Table 3. The number of exceedances in the region varies between 6 and 45 in the region with the mean of 24 days during PLD. During LDM the exceedance numbers varies between 1 and 26 days with the average of 15 days. The average exceedance number of the region during LDM declined 47% with respect to PLD. Maximum decline in exceedance number was observed in Istanbul with the value of 92%. There is also an increment in exceedance numbers in some stations. Tekirdağ observed the maximum increment during LDM with respect to PLD with the value of 133%. Overall, metropolitan cities experienced decline of exceedance numbers, while small cities experienced both decline and increment.

The mean concentrations of PM_{10} during subLDM periods are seen in Table 4. All the stations experience a decline of PM_{10} during FLD with respect to RFLD days, with the region average of 25%. The decline rates vary between 17 and 39%. Kocaeli and Yalova are the stations with smaller declines of 17 and 20%. Yalova is not a metropolitan city, so the decline is smaller here because a full lockdown on weekends is not applied in small cities. The Kocaeli station is located near the industrial areas so the decline is the lowest since the factories did not close during lockdown measures. There are two cement and metal factories within a 5-km distance of Kocaeli station. The higher decline in values is observed at the Tekirdağ and Sakarya stations with 39 and 28%. Even though Tekirdağ and Sakarya are metropolitan cities in which lockdown measures were undertaken, the

Table 3 The exceedance number of PM_{10} limits during PLD and LDM

	Balı	Bilec	Bursa	Cana	Edir	İsta	Kırk	Koca	Saka	Teki	Yalo
PLD	29	6	45	19	49	12	32	21	40	6	10
LDM	6	6	26	18	22	1	15	25	20	14	15

Table 4 The average PM_{10} concentrations during subLDM periods, FLD and RFLD, and change of mean PM_{10} concentrations during FLD with respect to RFLD

	Average (FLD) (μg/m^3)	Average (RFLD) (μg/m^3)	Rate of change (%)
Balıkesir	21.1	28.1	−25
Bilecik	20.8	27.0	−23
Bursa	31.7	43	−26
Çanakkale	31.6	41.8	−24
Edirne	34.5	45.3	−24
İstanbul	19.6	25.6	−23
Kırklareli	29.8	38.2	−22
Kocaeli	33.7	40.7	−17
Sakarya	28.7	39.8	−28
Tekirdağ	19.9	32.8	−39
Yalova	27.4	34.2	−20

Table 5 The average PM_{10} concentrations during LDM and the same period of the previous 4 years, and the change of concentrations during LDM with respect to the previous 4 years

	Average LDM (2020)	Average of March 17–June 1 of previous 4 years (2016–2019)	Rate of change (%)
Balıkesir	26.7	38.8	−31
Bilecik	25.7	44.5	−42
Bursa	40.6	76.2	−38
Çanakkale	40.1	32	+25
Edirne	43.1	41.8	+3
İstanbul	23.9	44.2	−46
Kırklareli	36.4	61.5	−40
Kocaeli	39.3	55.6	−29
Sakarya	37.5	54.4	−31
Tekirdağ	31.1	49.7	−37
Yalova	32.9	66.4	−51

population of these two cities is relatively lower compared to the other metropolitan cities in the region.

Lastly, the change rate for the average PM_{10} concentration during the LDM with respect to the mean PM_{10} concentrations during the same period for the previous 4 years are investigated. All the stations except Edirne and Çanakkale experienced a decline during the LDM (Table 5) with the region average of decline 29%. The decline rates fluctuate between 29 and 51%. Kocaeli and Sakarya are the stations with the smallest decreases, 29 and 31%, respectively, while İstanbul and Yalova experienced the largest declines, 46 and 51%, respectively. Çanakkale and Edirne exhibited different behaviors than

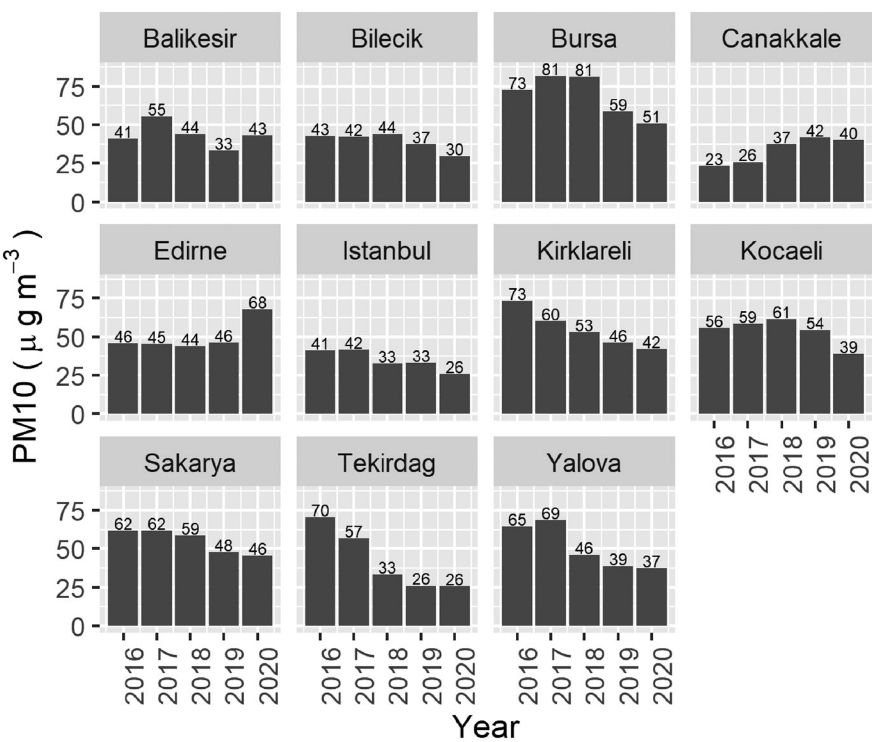

Fig. 3 The annual mean concentrations of PM_{10}

the other stations. They experienced increases during 2020 with respect to the long-term mean. The reason for the increase at Çanakkale is the replacement of the air quality station. The influence of dust transport at the Edirne station during the LDM can be seen in the rate of change.

The annual mean PM_{10} concentration for 2016–2020 for all the stations is seen in Fig. 3. As seen in Fig. 3, the annual mean PM_{10} concentration of 2020 is lower than the mean of the previous 4 years for all the stations except Balıkesir, Canakkale, and Edirne. The annual mean concentrations of PM_{10} of 2020 are the same for the previous 4 years for Balıkesir, while it is higher for Canakkale and Edirne. The annual mean PM_{10} concentration of 2020 is also lower than that of 2019 for all the stations, except Balıkesir, Edirne, and Tekirdag. Balıkesir and Edirne have higher PM_{10} concentrations in 2020 than in 2019, while Tekirdag has the same levels for 2 years.

$PM_{2.5}$ concentration

The daily $PM_{2.5}$ concentrations during the PLD, LDM, and ALD are shown in the time series located on the outer part of Fig. 4. The blue arrows indicate the decline of $PM_{2.5}$ during the LDM and ALD with respect to PLD, while the red arrows indicate increases. As seen in Fig. 4, all the stations are experiencing a decline in PM2.5 concentrations during both the LDM and ALD periods. Although the PM10 analysis shows mixed results, it is not a good indicator to show the efficiency of the lockdown measures. PM_{10} is related to traffic emissions but mass measurement techniques do not always capture this influence (Kendrick et al., 2015). $PM_{2.5}$ and NO_2 are the key parameters

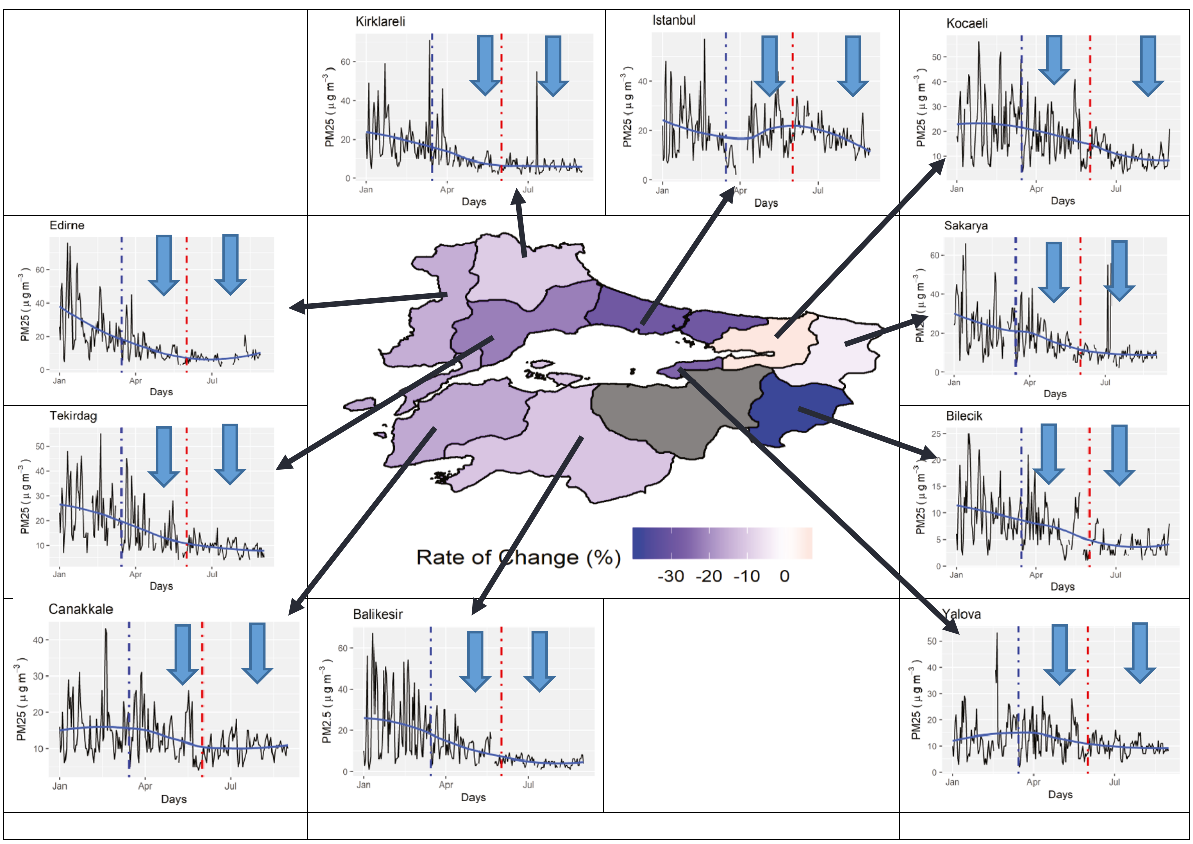

Fig. 4 (**a**) Time series located outer of the graph, represent the daily mean $PM_{2.5}$ concentrations for the period of January 1–August 31, 2020. (**b**) Inner map represents the change of mean $PM_{2.5}$ concentrations during LDM with respect to mean $PM_{2.5}$ concentrations of the same period of the previous year.

Table 6 As in Table 2, except for $PM_{2.5}$

	Average (PLD) (μg/m^3)	Average (LDM) (μg/m^3)	Rate of change (%)	Average (ALD) (μg/m^3)	Rate of change (%)
Balıkesir	23.7	11.8	−50	4.8	−79
Bilecik	9.9	7.2	−27	3.9	−60
Çanakkale	15.4	13.5	−12	10.4	−32
Edirne	26.6	12.3	−50	7.7	−71
İstanbul	21.0	18.4	−12	18.1	−13
Kırklareli	20.0	10.4	−48	6.7	−66
Kocaeli	23.7	17.5	−26	10.2	−56
Sakarya	24.1	16.6	−31	9.9	−59
Tekirdağ	23.6	15.0	−36	9.1	−61
Yalova	14.2	12.9	−9	9.8	−30

for traffic-related pollution as it could be affected more than PM_{10} by these lockdown measures.

The rate of decrease in $PM_{2.5}$ for all stations during the LDM with respect to PLD fluctuates between 9 (Yalova) and 50 (Balıkesir) percent (Table 6), with the region average of 30%. Çanakkale, İstanbul and Yalova are the stations that experience smaller declines by 12, 12, and 9%, respectively. Balıkesir, Edirne, and Kırklareli experienced the highest declines by 50, 50, and 48%, respectively. The rate of change for each station is quite sensitive to the station location during the LDM. For example, the İstanbul station is located on one of the main roads of the city which is used by many vehicles outside for essential purposes. All the cities in the region showed decline during LDM with respect to PLD. Lian et al. (2020) found the similar result with the mean decline of $PM_{2.5}$ about 20%, for the stations in Wuhan City, China. On the other hand, Adams (2020) concluded that $PM_{2.5}$ concentrations did not change significantly during lockdown measures, in the cities of Ontario, Canada. They emphasized that this result is related to the source profile of the stations.

All the stations experienced a decline during ALD with respect to PLD (Table 6). The decline rate varied between 13 (İstanbul) and 79 (Balıkesir) percent, with the region average of 53%. İstanbul, Çanakkale, and Yalova have the smallest declines at 13, 32, and 30%, respectively while Balıkesir, Edirne, and Kırklareli have larger declines of 79, 71 and 66%. The rate of change during the ALD is greater than the rate of change during the LDM. Although the location dependency for the rate of change at each station is valid, the rate of change is almost doubled due to additional seasonal effects.

The exceedance number of $PM_{2.5}$ limits during PLD and LDM is seen in Table 7. The number of exceedances in the region varies between 11 and 59 in the region with the mean of 41 days during PLD. During LDM, the exceedance numbers vary between 2 and 41 days with the average of 23 days. The average exceedance number of the region during LDM declined 44% with respect to PLD. All the stations experienced decline of exceedance numbers during LDM with respect to PLD. Maximum decline in exceedance number was observed in Bilecik with the value of 82%.

The average concentrations of $PM_{2.5}$ during the subLDM periods are seen in Table 8. All the stations experience declines of $PM_{2.5}$ during FLD with respect to RDLM days, with the region average of 17%. The decline rates vary between 5 and 30%. İstanbul and Yalova are the stations with smaller declines, both locations at 5%. Yalova is not a metropolitan city, so the decline is smaller. İstanbul is a constant pollution source of $PM_{2.5}$. The highest decline values are observed at the Çanakkale and Kırklareli stations with 25 and 30%, respectively. In small cities the

Table 7 As in Table 3, except for $PM_{2.5}$ concentrations

	Balı	Bilec	Cana	Edir	İsta	Kırk	Koca	Saka	Teki	Yalo
PLD	45	11	29	59	43	44	50	51	51	28
LDM	17	2	27	14	37	11	41	35	21	25

Table 8 The average $PM_{2.5}$ concentrations during subLDM periods, FLD and RFLD, and change of mean $PM_{2.5}$ concentrations during FLD with respect to RFLD

	Average (FLD) (μg/m^3)	Average (RFLD) (μg/m^3)	Rate of change (%)
Balıkesir	10.1	12.2	−17
Bilecik	5.9	7.5	−21
Çanakkale	10.7	14.2	−25
Edirne	10.5	12.7	−17
İstanbul	17.7	18.6	−5
Kırklareli	7.7	11.1	−30
Kocaeli	15.3	18.1	−15
Sakarya	14.3	17.2	−17
Tekirdağ	13.2	15.2	−13
Yalova	12.4	13.0	−5

Table 9 Average $PM_{2.5}$ concentrations during LDM and the same period of the previous year and the change of concentrations during LDM with respect to the previous year

	Average LDM μg/m^3) (2020)	Previous year average of same period (μg/m^3)	Rate of change (%)
Balıkesir	11.8	13.2	−11
Bilecik	7.2	11.8	−39
Çanakkale	13.5	16.0	−16
Edirne	12.3	14.4	−15
İstanbul	18.4	26.0	−29
Kırklareli	10.4	11.6	−10
Kocaeli	17.5	16.5	+6
Sakarya	16.6	17.9	−4
Tekirdağ	15.0	19.2	−22
Yalova	12.9	17.5	−26

people obey the lock-down measures spontaneously, and this result is seen in the air quality measurements. Even though, there is no decline in workplace mobility, the cause of decline in $PM_{2.5}$ can be the decline in other mobility types.

Lastly, the change rate for the mean $PM_{2.5}$ concentration during the LDM with respect to the mean $PM_{2.5}$ concentrations during the same period for the previous year (2019) are investigated. All the stations except Kocaeli experienced a decline during the LDM (Table 9), with the region average of 16.5% decrease. The decline rates fluctuate between 4 and 39%. Kırklareli and Sakarya are the stations with the smallest decline at 10 and 4%, respectively, while Bilecik and İstanbul experienced the greatest declines of 39 and 29%, respectively. Kocaeli exhibited different

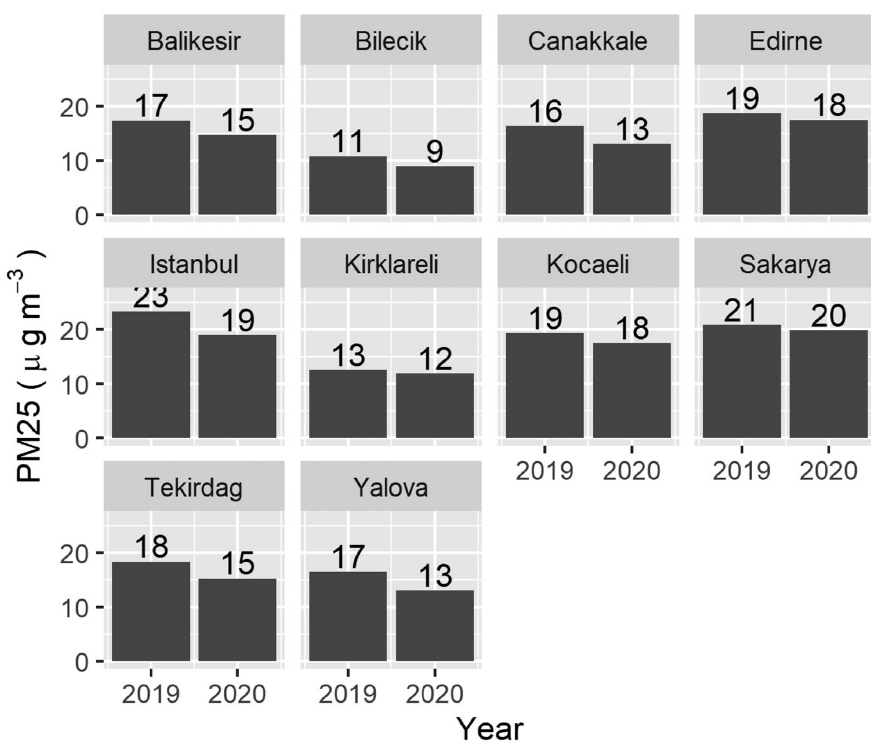

Fig. 5 The annual mean concentrations of $PM_{2.5}$

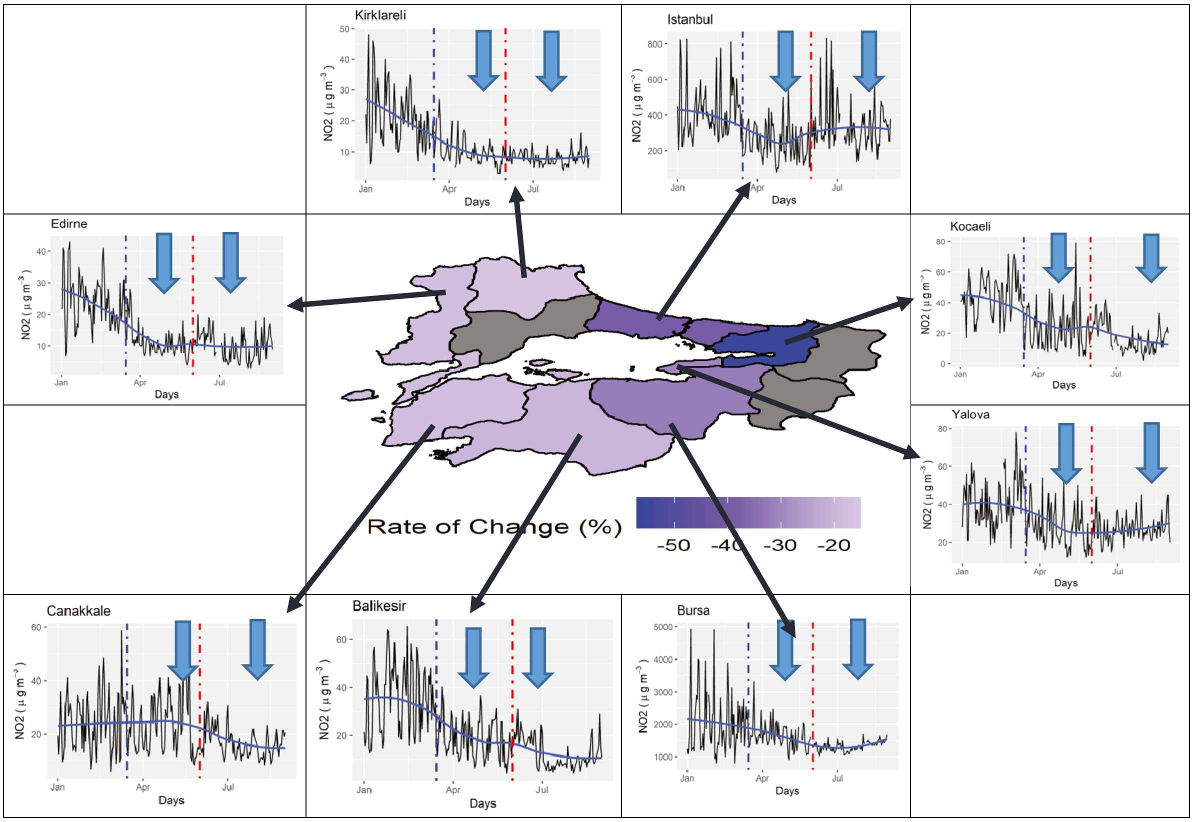

Fig. 6 Same in Fig. 3, except for NO_2

behaviors than other stations as $PM_{2.5}$ increased during 2020 with respect to the same period in 2019 at 6%.

The annual mean $PM_{2.5}$ concentration for 2019–2020 for all the stations is seen in Fig. 5. As seen in Fig. 5, the annual mean $PM_{2.5}$ concentration of 2020 is lower than the mean of 2019 for all the stations. The lowest decline belongs to the Sakarya station with the value of 5%, while the highest belongs to the Yalova station with the value of 24%.

NO_2 concentrations

The daily NO_2 concentrations for PLD, LDM, and after-lockdown ALD are shown in the time series located on the outer part of Fig. 6. The blue arrows indicate a decline during the LDM and ALD with respect to PLD, while the red arrows indicate increases. As seen in Fig. 6, all the cities experience

Table 10 As in Table 2, except for NO_2

	Average (PLD) (μg/m^3)	Average (LDM) (μg/m^3)	Rate of change (%)	Average (ALD) (μg/m^3)	Rate of change (%)
Balıkesir	35.2	17.8	−49	12.0	−65
Bursa	72.2	51.0	−29	43.8	−39
Çanakkale	23.9	23.5	−1	16.1	−32
Edirne	23.9	11.2	−53	10.2	−59
İstanbul	73.3	46.4	−37	51.7	−31
Kırklareli	21.2	10.1	−52	8.1	−62
Kocaeli	43.8	23.2	−47	17.1	−61
Yalova	41.3	27.6	−33	27.1	−34

Table 11 As in Table 3, except for NO_2

	Balı	Bursa	Cana	Edir	İsta	Kırk	Koca	Yalo
PLD	50	74	35	30	56	19	69	68
LDM	16	65	31	2	62	1	31	39

a decline of NO_2 concentrations during both the LDM and ALD periods that is consistent with Lian et al. (2020), Adams (2020), and further studies. Lian et al. (2020) found a decrease of 53% for the cities in Hubei province, China, and Adams found a significant evidence for decline of nitrogen dioxide and nitrogen oxides for the stations in Ontario, Canada.

The rate of decrease for all the stations during the LDM with respect to PLD fluctuates between 29 (Bursa) and 53 (Edirne) percent except for the Çanakkale station (Table 10). The Çanakkale station experienced only a decline of 1%, with the region average of 38%. Bursa and Yalova are the stations that experience smaller declines at 29 and 33%, respectively. The Edirne and Kırklareli stations observe larger decreases of 53 and 52%, respectively.

The significant decreases were observed during the ALD, as seen in Fig. 4 and Table 10 in the range of 31 (İstanbul) and 65 (Balıkesir), with the region average of 48%. Four of the nine NO_2 stations experienced declines between 31 and 39%, while others experienced more than 59%.

The exceedance number of NO_2 limits during PLD and LDM is seen in Table 11. The number of exceedances in the region varies between 19 and 74 in the region with the mean of 50 days during PLD. During LDM, the exceedance numbers vary between 1 to 65 days with the average of 30 days. The average exceedance number of the region during LDM declined 53% with respect to PLD. There is also an increment in exceedance numbers in only one station. İstanbul observed the maximum increment during LDM with respect to PLD with the value of 11%. Maximum decline in exceedance number was observed in Kırklareli with the value of 93%.

The average concentrations of NO_2 during the sub-LDM periods are seen in Table 12. All the stations experience declines in NO_2 during FLD with respect to RDLM days, with the average of 27%. The decline rates vary between 4 (Çanakkale) and 42 (Bursa) percent. Çanakkale and Yalova are the stations with smaller declines at 4 and 20%, respectively. As stated above, these cities are not metropolitan cities, which resulted in smaller declines. Higher declines are observed at the Bursa and Kocaeli stations, 42 and 39%, respectively. These stations are traffic-heavy stations, and the full lockdown led to the decrease of the traffic emissions in these cities.

Lastly, the change in the mean NO_2 concentration during the LDM with respect to the mean NO_2 concentrations during the same period of the previous year (2019) are investigated. All the stations experienced a decline during the LDM (Table 13). The declines varied between 16 and 56%, with the average of 29%. Çanakkale and Kırklareli are the stations with the smallest declines of 16 and 18%, respectively, while İstanbul and Kocaeli experience the largest declines at 40 and 56%, respectively. The

Table 12 As in Table 8, except for NO_2

	Average (FLD) (μg/m^3)	Average (RFLD) (μg/m^3)	Rate of change (%)	Average LDM (μg/m^3)	Previous year average of same period (μg/m^3)	Rate of change (%)
Balıkesir	13.1	19.0	−31	17.8	22.2	−20
Bursa	32.3	56.0	−42	51.0	74.9	−32
Çanakkale	22.7	23.7	−4	23.5	28.6	−18
Edirne	8.1	11.9	−32	11.2	13.7	−18
İstanbul	34.7	49.3	−24	46.4	77.3	−40
Kırklareli	7.5	10.7	−30	10.1	12.1	−16
Kocaeli	15.3	25.1	−39	23.2	53.1	−56
Yalova	23.1	28.7	−20	27.6	39.4	−30

Table 13 As in Table 9, except for NO_2

	Average LDM (μg/m³)	Previous year average of same period (μg/m³)	Rate of change (%)
Balıkesir	17.8	22.2	−20
Bursa	51.0	74.9	−32
Çanakkale	23.5	28.6	−18
Edirne	11.2	13.7	−18
İstanbul	46.4	77.3	−40
Kırklareli	10.1	12.1	−16
Kocaeli	23.2	53.1	−56
Yalova	27.6	39.4	−30

same patterns as discussed above are the explanation for these results. Less crowded cities demonstrated lower declines because full lockdown measures were not undertaken in them. On the other hand, more crowded cities experienced higher declines due to the full lockdown measures.

The annual mean NO_2 concentration for 2019–2020 for all the stations is seen in Fig. 7. As seen in Fig. 7, the annual mean NO_2 concentration of 2020 is lower than the mean of 2019 for all the stations, except Balıkesir and Kırklareli. The NO_2 level increased in 2020 compared to 2019 with the value of 5 and 7% for Balıkesir and Kırklareli, respectively. The highest declines are observed in the large cities. Bursa, İstanbul, and Kocaeli have the highest decline rates with the values of 16, 16, and 47%, respectively.

Mobility data

The time series of the mobility data and daily average PM_{10}, $PM_{2.5}$, and NO_2 concentrations for each of the cities during the LDM period are seen in Fig. 8.

As seen in Fig. 8, the higher the population, the greater the decrease in mobility. The peak values in the figures for the metropolitan cities are seen during the full lockdown (FLD) days. The last peak value that can be seen in all the cities was occurred during the lockdown which was applied for the whole country. There are declines in the mean concentrations of all pollutants at different levels for all the stations during these peaks.

Figure 8 shows an important change in work mobility after the lockdown measures were implemented. Overall average of work mobility decline during LDM for each city is around 50%. It can be seen from Fig. 8 the decline of NO_2 increases when FLD measures are applied in metropolitan cities. On

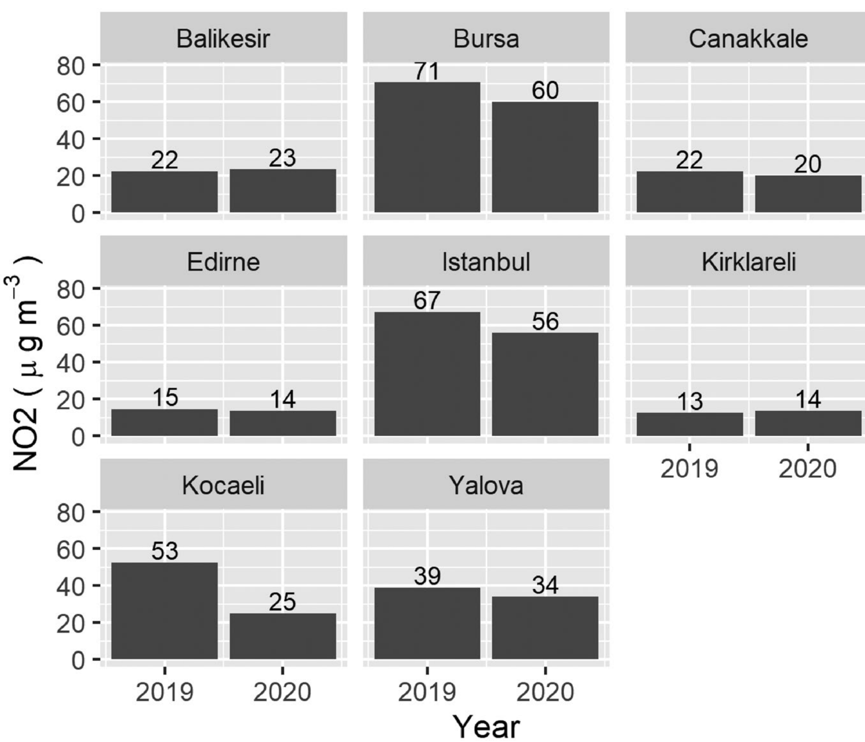

Fig. 7 The annual mean concentrations of NO_2

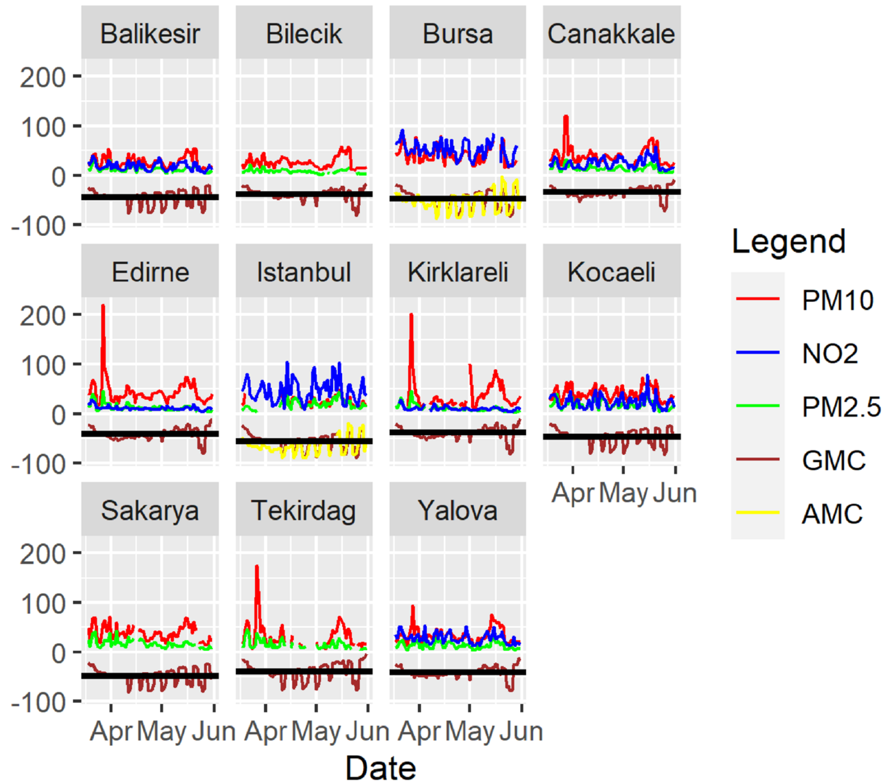

Fig. 8 Time series of the mobility during the LDM with respect to 1 January–16 February 2020 for the stations used in this study (negative values in y axis; yellow mobility lines represent the mobility change for Istanbul and Bursa by Apple (AMC represents Apple mobility change); brown mobility lines represent the mobility change for all the stations (GMC represents Google mobility change); black line represents the average mobility change during LDM period) and PM_{10} (red), $PM_{2.5}$ (green), and NO_2 (blue) concentrations during LDM (positive values)

the other hand, PM_{10} and $PM_{2.5}$ concentrations do not respond to the mobility declines. The daily mean number of cars for a location in Istanbul is 6250 and 3750 for the period before PLD and FLD, respectively. The decline in the vehicle numbers is 40% which is almost identical to the decline in the Google mobility data of Istanbul.

The correlations between mobility change and pollutant concentrations were calculated and tested via Pearson's test, and the results are shown in Table 14.

The correlation coefficient between mobility and PM_{10} varies between 0.12 (Kocaeli) and 0.30 (Bursa). None of the correlation coefficient is statistically significant. The correlation coefficients between Apple mobility data and PM_{10} concentration are 0.27 and 0.19 for Bursa and Istanbul, respectively, and they are not statistically significant. The correlation coefficients between mobility and $PM_{2.5}$ vary between 0.04 (Edirne) and 0.12 (Canakkale). None of the correlation coefficient is statistically significant. The

Table 14 Pearson's correlation coefficients between work mobility dec and pollutant concentrations

Correlation coefficient	Balıkesir	Bilecik	Bursa	Canakkale	Edirne	İstanbul	Kırklareli	Kocaeli	Sakarya	Tekirdağ	Yalova
PM_{10}	0.13	0.19	0.30 (0.27)	0.13	0.17	0.28 (0.19)	0.19	0.12	0.21	0.14	0.15
$PM_{2.5}$	0.06	0.08	-	0.12	0.04	−0.07 (0.03)	0.07	0.11	0.09	0.01	0.06
NO_2	0.40**	-	0.64** (0.54**)	0.29	0.38**	0.45** (0.40)**	0.30**	0.47**	-	-	0.25*

NS denotes two samples are not significant correlated ($p \geq 0.05$). The values in the parentheses for Istanbul and Bursa are the correlation coefficients between driving mobility provided by Apple and pollutant concentrations

*denotes correlations between two samples are significant at the levels of $0.001 \leq p < 0.01$

**denotes correlations between two samples are significant at the levels of $p < 0.001$

correlation coefficient between Apple data and $PM_{2.5}$ concentration is 0.03 for Istanbul. All the correlation coefficients between mobility changes and both PM_{10} and $PM_{2.5}$ are smaller than 0.30, and they are not statistically significant for all the stations which means there is no correlation between mobility and PM_{10} and $PM_{2.5}$. On the other hand, NO_2 is highly correlated to mobility compared to PM_{10} and $PM_{2.5}$. Correlation coefficients vary between 0.25 and 0.64. Yalova and Canakkale have lower correlation coefficients which vary between 0.25 and 0.64. Yalova and Canakkale have lower correlation coefficients of 0.25 and 0.29, respectively. Bursa and Kocaeli have higher correlation coefficients of 0.64 and 0.47, respectively. The correlation coefficient between the Apple data and NO_2 concentration in Bursa and İstanbul are 0.54 and 0.40, respectively, which are statistically significant. All the correlation coefficients greater than 0.30 are statistically significant, *p*-value greater than 0.001, while the correlation coefficient of Yalova is statistically significant with a *p*-value greater than 0.01. The correlation coefficient of Çanakkale is not significant. In general, large cities have a greater correlation coefficient than the small cities.

Conclusion

The outbreak of the novel coronavirus (COVID-19) has changed the daily routines of people around the world. The first case was confirmed in Turkey on 11 March 2020. The relevant authorities first shut down airway transportation and, then the borders. The schools are closed and online education started. Stay-at-home orders, social distance measures and lockdown measures were applied. However, in spite of these measures, the number of cases reached 4500 per day by 10 April. Since then, the government announced that in cities from 10 April to June 1, more restrictive measures will be imposed on 31 major cities. The change in concentrations of PM_{10}, $PM_{2.5}$, and NO_2 during these measures with respect to the pre-lockdown period, the same period in the previous years and for different levels of measures for the cities in Marmara Region of Turkey were investigated in this study. The daily mean concentrations of PM_{10}, $PM_{2.5}$, and NO_2 obtained from 11 stations operated by the Ministry of Environment and Urbanization and Google mobility data are used in this study. The main findings are listed below:

1. Eight of the 11 stations experienced decline of average PM_{10} concentrations during the lockdown period compared to the pre-lockdown period with a change rate between 14 and 30%. Similarly, the average PM_{10} concentrations after lockdown decreased with respect to the pre-lockdown in 8 of the 11 stations (not the same stations). The strict lockdown measures decreased the PM_{10} levels in all the stations. Nine of the 11 stations experienced decline in the lockdown period with respect to the average of the same period in the previous 4 years with varying ratios of 29 to 51%.
2. $PM_{2.5}$ concentrations in all the stations decreased during lockdown measures with respect to the pre-lockdown with the rate of 9 to 50%. During the after-lockdown period, decline values varied between 13 and 79% with an increase in one station. $PM_{2.5}$ concentrations decreased with district measures with varying rates between 5 and 30%. The decrease in concentrations of $PM_{2.5}$ during the lockdown measures with respect to the previous year vary between −4 and 39%, except Kocaeli. It experienced increment with the rate of 6%.
3. All the stations experienced decline of NO_2 concentrations during the lockdown-measure period and after-lockdown period with respect to the pre-lockdown period. The rates vary between 1 and 53% during lockdown and 31 to 65% during the after lockdown. District measures affected NO_2 concentrations as well. NO_2 concentrations decreased in all the stations at a varying rate of 4 to 42%. The decrease in the concentrations of NO_2 with respect to the previous year varies between 16 and 56%.
4. No correlation emerged between mobility and both PM_{10} and $PM_{2.5}$ for none of the cities. On the other hand, the correlation coefficients between mobility reduction and NO_2 concentration vary between 0.25 and 0.64. All the correlation coefficients greater than 0.30 are statistically significant with a *p*-value greater than 0.001. Apple data gave similar results for Bursa and Istanbul.

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Data availability The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Conflict of interest The author declares no competing interests.

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