



The impact of COVID-19 lockdown on the air quality of Eastern Province, Saudi Arabia

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Received: 9 August 2020 / Accepted: 21 August 2020
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Abstract

Since the identification of the COVID-19 outbreak in Wuhan, China, in December 2019, the death toll from the direct infection by COVID-19 has exceeded 775,000, and more than 21 million cases have been reported to the World Health Organization (WHO) around the world. It is strongly believed that its impact might be worsened by poor outdoor and indoor air qualities, particularly on older adults. The nationwide lockdown measures were imposed between March 23 and June 20, 2020, to stop the spread of COVID-19 pandemic in the Kingdom of Saudi Arabia (KSA). In this work, the possible effects of the lockdown on the air quality were investigated using meteorological and air quality datasets obtained from eight monitoring stations covering the Eastern Province of the KSA. The studied air pollutants include carbon monoxide (CO), sulfur dioxide (SO₂), nitrogen dioxide (NO₂), ozone (O₃), and inhalable particulate matter (PM₁₀). The NO₂ was found to be the marker pollutant responding best to the lockdown measures since its concentrations decreased at all sites during- and post-lockdown periods and ranged between 12–86% and 14–81%, respectively. Compared with pre-lockdown period, the Eastern Province also experienced significant concentration reductions at varying rates for PM₁₀ (21–70%), CO (5.8–55%), and SO₂ (8.7–30%), while O₃ concentrations showed increasing rates ranging between 6.3 and 45%. The consequences of these reductions were reflected in easing the outdoor air quality, which might reduce the impact of COVID-19 pandemic, especially on elderly and sensitive groups.

Keywords COVID-19 · Sars-Cov-2 · Lockdown · Air pollution · Air quality · Saudi Arabia

Introduction

The World Health Organization (WHO) announced on Wednesday, March 11, 2020, the new coronavirus “COVID-19” disease as “a global epidemic” (WHO 2020). In response to that, governments around the world have been taking a range of actions and measures, including the closing of schools, worship places, and workplaces, postponing and canceling huge public events, restricting public transport, the lockdown of movement of people, and ceasing domestic and international flights (Bherwani et al. 2020; Bashir et al. 2020a). According to many studies, the COVID-19 is believed to transmit through airborne bioaerosol droplets. Nevertheless, different parameters such as the extent of urban air pollution and weather conditions might have a significant

impact on the elevated rates of COVID-19 cases (Farhan Bashir et al. 2020; Fareed et al. 2020).

After the discovery of the first case of COVID-19 in the KSA on March 2, 2020, a series of actions were taken in response to the COVID-19 pandemic. The first three significant actions taken to control the spread of the pandemic were as follows: (i) suspension of Umrah pilgrimage (March 4), (ii) suspension of all schools and universities (March 8), and (iii) suspension of all international flights (March 9). With the spread of COVID-19 and the absence of vaccine and medication globally, the Saudi government imposed nationwide partial lockdown (from 7 PM to 6 AM) on March 23 followed by the restriction on movement between provinces on March 25. After that, the full lockdown was imposed nationwide on April 6. On May 28, the lockdown was partially lifted in all cities except Mecca, the movement between regions was eased, and shopping malls were opened. Following this, prayers were allowed in mosques except for the Great Mosque of Mecca, and the restrictions on domestic flights, restaurants and cafes, and parks were eased on May 31. The latest action was on June 21, where the partial lockdown was lifted on all regions. However, international flights remain

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suspended except repatriation flights for residents. Lastly, the Pilgrimage (Haj) was allowed to domestic residents and Saudi nationals only with limited numbers (MoH 2020).

The COVID-19 lockdown measures affected many aspects of human activities including vehicle use, public transportation, and industrial processes (Pata 2020; Gautam 2020; Bashir et al. 2020b; Shehzad et al. 2020). In addition, several researchers around the world reported that there is a mitigation of air pollution during COVID-19 lockdown compared with before period. For instance, Berman and Ebisu (2020) assessed the air quality during the COVID-19 pandemic using air quality data, including PM_{2.5} and NO₂, monitored in the USA between 2017 and 2020. The study found that statistically significant PM_{2.5} and NO₂ reductions were noticed as 11% and 26%, respectively. Shakoor et al. (2020) investigated the changes in levels of air pollutants before and after lockdown periods in USA and China. The results showed that CO, NO₂, and PM_{2.5} concentration reduced by 19%, 37%, and 1.1%, respectively in USA, while CO, NO₂, SO₂, PM_{2.5}, and PM₁₀ concentration decreased by 27%, 39%, 18%, 18%, and 38%, respectively, in China. Agarwal et al. (2020) found that lockdown measures in India and China resulted in improvements for the air quality indexes of PM_{2.5} and NO₂ by 65% and 66% in India and 45% and 37% in China, respectively. Singh and Chauhan (2020) analyzed air quality changes before and after COVID-19 lockdown measures over India using ground-level and satellite observations. Their results demonstrated that the PM_{2.5} concentrations dropped by to 35%, compared with pre-lockdown phase. In another study, Sharma et al. (2020) studied the changes in concentrations of air pollutants before and after lockdown periods in seven cities of India. They reported that PM_{2.5}, PM₁₀, NO₂, and SO₂ reduced by 23–58%, 24–44%, 30–64%, and 3.5–70%, respectively. Zambrano-Monserrate and Ruano (2020) reported that NO₂ and PM_{2.5} levels in Ecuador importantly reduced just after the implementation of lockdown measures. At the regional scale, researchers studied the effect of climatic parameters on the spread of COVID-19. Their result showed that transportation and population numbers have a forward association with the infection rates (Barbieri et al. 2020; Ahmadi et al. 2020).

This study focuses on investigating the possible effects of the lockdown due to the COVID-19 pandemic on the air quality using meteorological and air quality datasets in the Eastern Province of the KSA.

Methodology

Description of the study area

The Eastern Province is the easternmost of the thirteen provinces of the KSA and located between latitudes of 29.16° N

and 19.11° N and longitudes of 44.65° E and 55.66° E. The Eastern Province is the third most populated province with a total population of 4.9 million and the largest province (by area) of the KSA. The weather is hot in the summer season and mild for the rest of the seasons of the year. The long-term annual average values of the temperature and relative humidity are 27 °C and 41%, respectively. Wind systems from northern directions dominate over the area with an average ground-level wind speed of 4.2 m/s. The region has an arid precipitation regime and receives a total of 100 mm rainfall in a year between November and April (Anil et al. 2019). The Eastern Province has been facing severe local and long-range dust storms because of the pressure gradients. During the summer season, hot, dry, and low-level northwesterly winds called “Shamal winds” blowing at a minimum speed of 10 m/s lift dust and sand to the local and remote regions (Karaca et al. 2009; Anil et al. 2017, 2019). Remarkable amounts of PM₁₀ have been inhaled during episodic periods, resulting in a tremendous rise in the number of hospital admissions regarding respiratory issues (Tsiouri et al. 2015). Tawabini et al. (2017) recently reported that the daily average PM₁₀ concentrations of Dhahran, Khobar, and Dammam districts of the Eastern Province were 177, 380, and 126 µg/m⁻³, respectively, which were quite above than the WHO’s daily PM₁₀ guideline value of 50 µg/m⁻³ (WHO 2006).

Air quality data and study period

The air quality dataset discussed in this research was obtained from the database of the General Authority of Meteorology and Environment Protection (GAMEP) including CO, SO₂, NO₂, O₃, and PM₁₀ in seven different locations of Eastern Province, which are Jubail (Station no. 1), Qatif (Station no. 2), Dammam (Stations nos. 3–5), and Al Ahsa (Stations nos. 7–8) cities. Furthermore, hourly concentrations of air pollutants have been measured and recorded at the fully automated mobile air quality monitoring station (Station no. 6) located inside the Dammam south campus of Imam Abdulrahman Bin Faisal University (IAU). The geographic locations of the air quality monitoring stations (AQMS) are given in Fig. 1. To reveal the impact of the lockdown due to the COVID-19 on the air quality, the obtained air quality datasets were divided into three periods: (i) pre-lockdown (September 15, 2019–March 22, 2020), (ii) during-lockdown (March 23, 2020–June 20, 2020), and (iii) post-lockdown (June 21, 2020–July 18, 2020).

Meteorology data

The meteorology data of the region during the study period was recorded by using a Davis® Vantage Pro 2+ wireless meteorology station, located at the roof of the college of engineering building of IAU (Station no. 6). The wind rose plots



Fig. 1 Locations of air quality monitoring stations in the Eastern Province

for the study region during the whole study, pre-lockdown, lockdown, and post-lockdown periods are illustrated in Fig. 2. The northwesterly winds governed the wind regime during the pre-lockdown, lockdown, and post-lockdown periods with the frequencies of 48.8%, 50.5%, and 58.6%, respectively. The average wind speeds of pre-lockdown, lockdown, and post-lockdown periods were calculated as 3.72 (± 2.35), 4.51 (± 2.77), and 3.92 (± 2.66) m/s, respectively.

Statistical analysis and data visualization

Descriptive statistics and outlier analysis methods were performed on the obtained air quality data sets. Box and whisker plots were depicted using the calculated mean, median, first quartile, third quartile, the range within 1.5 times of interquartile range (IQR), and outliers of each pollutant observed at each station for pre-lockdown, lockdown, and post-lockdown periods. Bivariate polar plots of concentrations were generated to determine the effect of wind velocity and wind direction data couple on the concentration of each pollutant during pre-lockdown, lockdown, and post-lockdown periods (Habebullah et al. 2015; Nadzir et al. 2020; Omokungbe et al. 2020).

Results and discussions

Concentration variations of air pollutants before, during, and after lockdown periods

Descriptive statistics of each pollutant such as mean, median, first quartile, third quartile, the range within 1.5 times of interquartile range (IQR), and outliers are represented in box and whisker plots for pre-, during-, and post-lockdown periods (Fig. 3). During the whole study period between September 15, 2019, and July 18, 2020, the mean and median CO concentrations ranged between 0.16 and 0.14 ppm (IAU-Urban station), respectively, and between 2.34 and 2.04 ppm (Dammam-Coastal), respectively, and were quite lower than the maximum daily 8-h mean value of European Union (Directive 2008/50/EC) (EU 2008). The observed CO concentrations indicated distinct spatial and temporal variation patterns before, during, and after lockdown periods. The highest CO concentration decrease during the lockdown was found for Qatif ($\downarrow 0.96$ ppm), followed by Rakah ($\downarrow 0.33$ ppm), Al Ahsa-Industrial ($\downarrow 0.24$ ppm), and IAU ($\downarrow 0.12$ ppm) sites as compared with the pre-lockdown period. On the other hand, the mean CO concentration at the Jubail site gradually increased by 0.50 ppm during the lockdown and 0.93 ppm

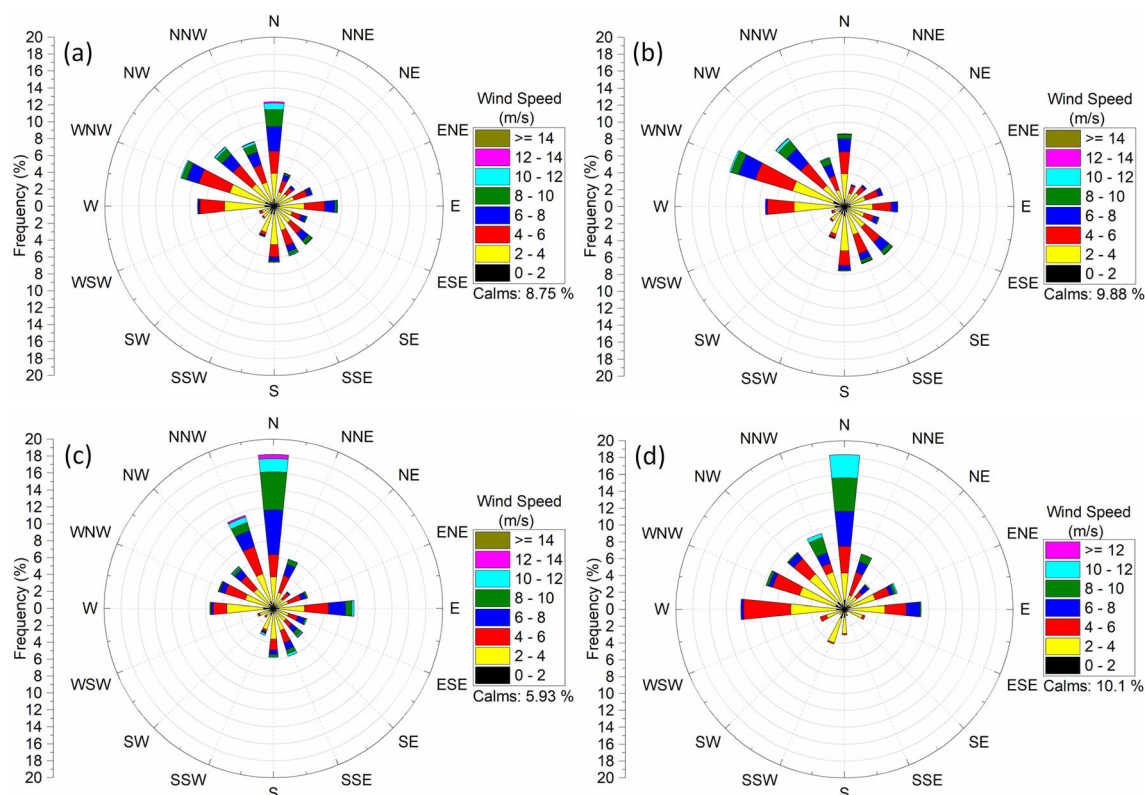


Fig. 2 Wind rose plots for the study region during: **a** the whole study, **b** pre-lockdown, **c** lockdown, and **d** post-lockdown periods

post-lockdown phases. In addition to this, mean CO concentrations at Rakah site before and after lockdown periods increased from 1.65 to 2.48 ppm. The fluctuations of mean CO concentrations at Al Ahsa-Traffic, Dammam-Coastal, and Dammam-Industrial stations were not statistically significant within pre-, during-, and post-lockdown periods.

As observed in CO concentrations, temporal and spatial changes of SO₂ concentrations were quite different. Almost all sites exhibited mild outlier values before, during, and after lockdown periods with an average of mild to extreme outliers of three points. Compared with the pre-lockdown period, the IAU site indicated the highest SO₂ concentration reduction (↓1.38 ppb) during the lockdown, followed by Qatif (↓0.64 ppb), Jubail (↓0.41 ppb), Dammam-Industrial (↓0.21 ppb), and Al Ahsa-Industrial (↓0.16 ppb) sites. On the contrary, in comparison with the pre-lockdown period, mean SO₂ concentrations gradually increased by 2.58 ppb (mean: 0.88 ppb) and 13.5 ppb (8.18 ppb) at Rakah and by 0.88 ppb (mean: 0.74 ppb) and 1.25 ppb (1.10 ppb) at Dammam-Coastal sites during the lockdown and post-lockdown phases, respectively. The highest SO₂ concentration increase during the lockdown was noticed for the Al Ahsa-Traffic site (↑3.39 ppb) as compared with the pre-lockdown period. As was observed for Rakah and Dammam-Coastal sites, the mean SO₂ concentrations within the post-lockdown phase at Al Ahsa-Traffic, Qatif, and Al Ahsa-Industrial sites increased by 2.55, 1.69, and 0.62 ppb,

respectively, with respect to the pre-lockdown period. It is noteworthy to mention that only the mean SO₂ concentration at the Rakah site during the post-lockdown period (41.9 μg/m⁻³) was higher than the WHO's daily SO₂ guideline value of 20 μg/m⁻³ (WHO 2006). The increased concentrations noticed for CO and SO₂ pollutants at few locations could be linked to the large spectrum of industrial activities generating variable emission rates since most of the essential facilities were not shut down during the lockdown period.

The impact of the lockdown period was most obvious on NO₂ concentrations over the Eastern Province. The mean NO₂ concentrations during pre-lockdown period were in the following order: 81.7 ± 82.8 ppb (Jubail) > 30.1 ± 20.6 ppb (Rakah) > 21.5 ± 5.43 ppb (IAU) > 8.85 ± 9.30 ppb (Al Ahsa-Traffic) > 5.49 ± 3.52 ppb (Dammam-Industrial) > 4.59 ± 2.64 ppb (Al Ahsa-Industrial) > 3.84 ± 0.68 ppb (Dammam-Coastal) > 3.29 ± 1.03 ppb (Qatif). At all monitoring sites, mean NO₂ concentrations considerably decreased during the lockdown and post-lockdown phases in reference to the pre-lockdown phase. The magnitude of decrease in mean NO₂ concentrations was as high as about 62.5 (median: 69.3), 25.1 (25.7), and 10.6 (11.3) ppb during the lockdown and 66.4 (median: 60.5), 18.5 (24.5), and 2.99 (4.10) ppb during the post-lockdown period for Jubail, Rakah, and IAU stations, respectively. As a result of this reduction trend because of the lockdown measures, the mean NO₂ concentrations in the pre-lockdown period at Jubail (155 μg/m⁻³), Rakah (57.2 μg/

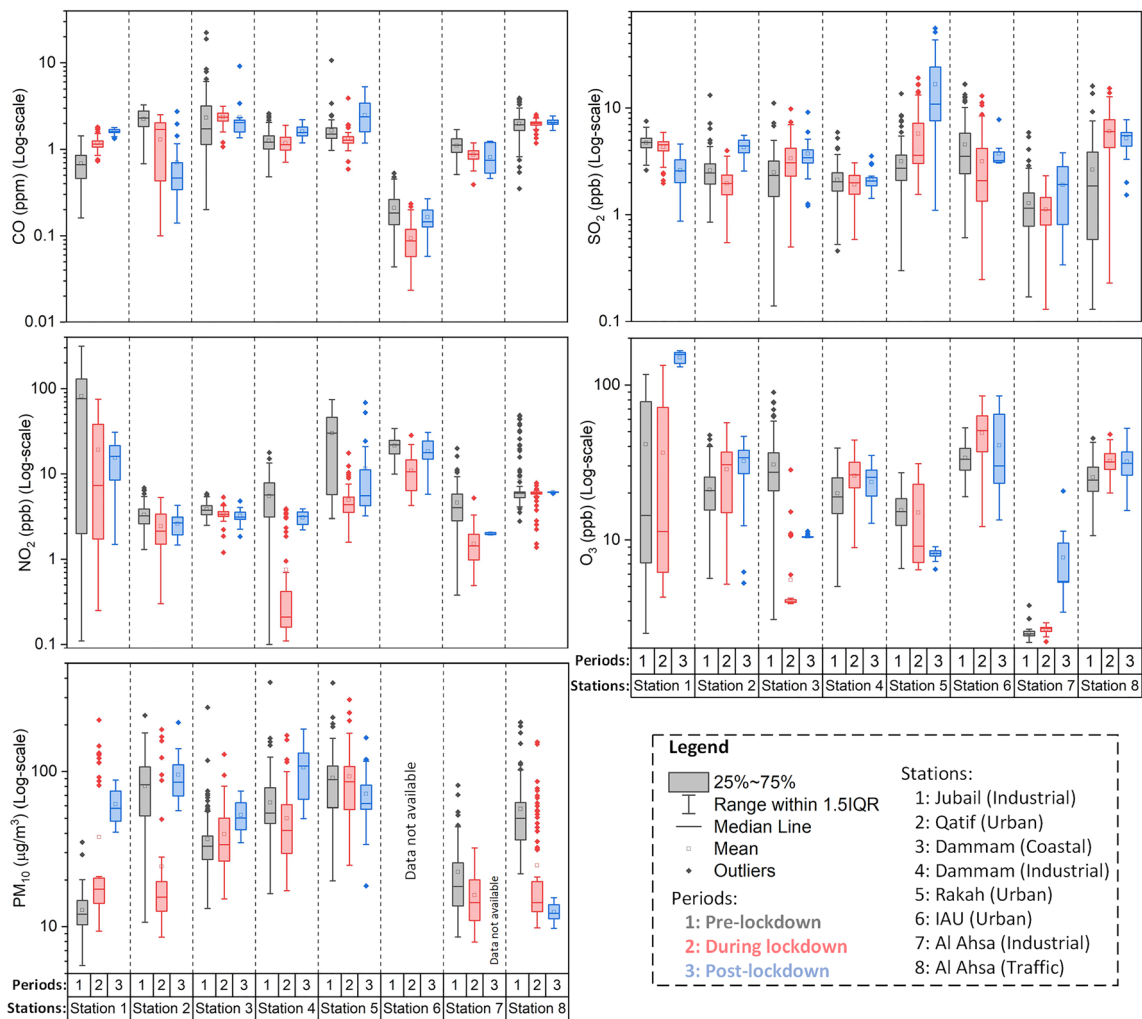


Fig. 3 Box and whisker plots of daily average CO, SO₂, NO₂, O₃, and PM₁₀ concentrations within the periods of pre-lockdown, during lockdown, and post-lockdown

m⁻³), and IAU (40.8 µg/m⁻³) sites, being higher than WHO's NO₂ guideline value of 40 µg/m⁻³, reduced to 27.8, 20.9, and 33.4 µg/m⁻³ even after the lockdown period. The other possible explanations for the NO₂ concentration decline rather than the significantly reduced transportation activities during the lockdown period might be attributed to the decrease in NO emission rate and/or the photolysis reaction of NO₂. The high combustion processes, including automobile engines, generally produce about > 80% of NO and < 20% of NO₂. Therefore, the photochemical reaction of NO₂ to produce O₃ and quite limited NO emissions to form NO₂ may be the reasons for the observed declines in NO₂ concentrations due to the lockdown.

Compared with the pre-lockdown phase, the mean O₃ concentration decreased considerably at the Dammam-Coastal site by ↓25.1 ppb and ↓20.1 ppb during and after lockdown phases, respectively. The mean O₃ concentration at Jubail site decreased from 46.5 ppb (median: 14.3 ppb) to 36.4 ppb (11.3 ppb) due to lockdown and after the lockdown increased

to 150 ppb (282 µg/m⁻³), which was quite above the WHO's 8-h daily maximum guideline value of 40 µg/m⁻³. In the other five monitoring sites, the mean O₃ concentrations during and after lockdown periods showed a clear upward trend at varying levels. This result is corroborated with recently published studies focused on the effect of lockdown measures to combat COVID-19 on the air quality of Delhi (India) (Mahato et al. 2020), Almaty (Kazakhstan) (Kerimray et al. 2020), Barcelona (Spain) (Tobias et al. 2020), São Paulo (Brazil) (Nakada and Urban 2020), Wuhan (China) (Lian et al. 2020), and Hangzhou (China) (Wang et al. 2020). In these cited studies, the increasing trend of O₃ against imposed lockdown measures was linked to (i) sharp drop of NO_x emissions in lockdown period decreasing the possibility of NO + O₃ titration reaction, (ii) increased VOC/NO_x ratio because of more reduced NO_x emission enhancing O₃ production, and (iii) stronger solar radiation compared with pre-lockdown period favoring O₃ formation and accumulation. These three explanations on why O₃ concentrations increased against

lockdown measures are also valid for the Eastern Province where: (i) NO₂ concentrations remarkably decreased at all sites, (ii) fugitive VOC emissions from continuously operating petrochemical/chemical manufacturing facilities and oil refineries, and (iii) increasing solar radiation throughout the season (pre-lockdown average: 7982 W/m² day; lockdown: 12,000 W/m² day; and post-lockdown: 13,681 W/m² day).

The PM₁₀ pollutant demonstrated the highest number of outliers among other pollutants during the whole study period. The number of PM₁₀ outliers (> 1.5IQR) during lockdown is the highest for Jubail, Qatif, and Al Ahsa-Traffic sites. In addition, the mean values were significantly above the median values for most of the PM₁₀ sampling locations during this study. The effect of lockdown on PM₁₀ pollution was most apparent on Qatif, Dammam-Industrial, and Al Ahsa-Traffic sites where the mean concentrations reduced from 80.3 (median: 82.2) to 24.4 (15.5) µg/m⁻³, from 63.0 (54.1) to 49.8 (41.9) µg/m⁻³, and from 57.4 (50.1) to 24.8 (13.7) µg/m⁻³, respectively, and became below the WHO's PM₁₀ guideline value of 50 µg/m⁻³. The mean PM₁₀ concentrations at Jubail, Dammam-Coastal, and Rakah sites did not indicate a decreasing trend during the lockdown, implying that these sites might be under the effect of a wide range of PM₁₀ emission sources.

Source apportionment of air pollutants by bivariate polar plots

Bivariate polar plots depicted in Fig. 4 illustrate the joint effect of wind velocity and wind direction on the levels of air pollutants monitored at Rakah station before, during, and after lockdown periods. The radius, angle, and colored contour on the polar graphs represent wind velocity (0–9 m/s), wind direction (0–360 in degrees), and concentration of the pollutant, respectively. The Rakah station was selected based on the extent of air pollution level relative to other stations. The main local air pollution sources in the vicinity of Rakah urban monitoring station are nearby traffic with moderate volume and extensive excavation/construction activities for the new residential area at southwest, King Abdulaziz Seaport in the north (4 km), and Industrial Area I at the west (4 km). Concentrations of CO and SO₂ indicated similar distribution patterns on bivariate polar plots. Northerly winds with moderate speed and southerly winds with low speed usually brought higher CO and SO₂ concentrations before and during the lockdown. After the lockdown, both CO and SO₂ concentrations remarkably increased, and high concentrations corresponding to the winds blowing from all directions with low speeds (< 4 m/s) point out local sources. The relatively calm and low-speed wind conditions compared with before and during lockdown might be the reason to carry plumes of a large number of vehicles and machinery operating at the nearby construction site using diesel fuel with high sulfur content. The NO₂ concentrations showed the maximum decrease

during the lockdown phase among other pollutants since the main source for NO₂ emissions is the on-road traffic, which was drastically reduced. The winds blowing from southwestern and northeastern sectors at varying speeds carried high NO₂ levels to the monitoring site before and after lockdown phases. The concentration contour distribution of O₃ demonstrated an opposite pattern to that of NO₂ within the pre-lockdown period due to the scavenging effect of NO₂ on O₃ (NO + O₃ titration reaction). The mean O₃ concentration during lockdown was almost the same as pre-lockdown and decreased by 7.21 ppb after the lockdown. This variation trend could be ascribed to the balanced VOC/NO_x ratio because of the VOC-limited characteristics of the Rakah area, which did not result in increasing O₃ concentrations during and after lockdown periods as observed for other five sites in the Eastern Province. PM₁₀ concentration distribution patterns on bivariate polar plots before and during lockdown were almost similar. The northwesterly and southerly winds with variable speeds carried high PM₁₀ emissions to the monitoring site. Within the whole study period, the highest PM₁₀ concentrations were observed when the wind speed was above 3 m/s, pointing the enhanced resuspension of dust and sand particles from open lands nearby and the possibility of regional/long-range transport. Interestingly, the mean PM₁₀ concentration during the post-lockdown period reduced by 19.2 µg/m⁻³ as compared with pre-lockdown, which could be explained by changes in source emission rates, meteorological conditions, and atmospheric stability at Rakah area.

Percent changes of air pollution levels during and after lockdown

The percent changes in the concentrations of criteria air pollutants monitored at each station during and after the lockdown in reference to before lockdown are depicted in Fig. 5. The air quality improvements at Qatif-Industrial, Dammam-Industrial, IAU-Urban, and Al Ahsa-Industrial sites were more evident as compared with the other three sites, and the response level of each site was quite different against same lockdown measures. The most pronounced decrease was found for NO₂ since NO₂ concentrations reduced at all sites during the lockdown and after lockdown as well. Within the lockdown phase, the highest NO₂ reduction rate was noticed at Dammam-Industrial site (86%), and followed by Rakah (84%), Jubail (77%), and Al Ahsa-Industrial (67%) while the reduction rates were less than 50% at other sites: IAU (49%) Al Ahsa-Traffic (34%), Qatif (26%), and Dammam-Coastal (12%). After the lockdown, NO₂ concentrations also dropped at all sites within the range between 14% (IAU) and 81% (Jubail).

In response to decreasing NO₂ emission during lockdown period, changes in CO concentrations demonstrated decreasing trends most obviously at IAU (55%) and Qatif (42%)

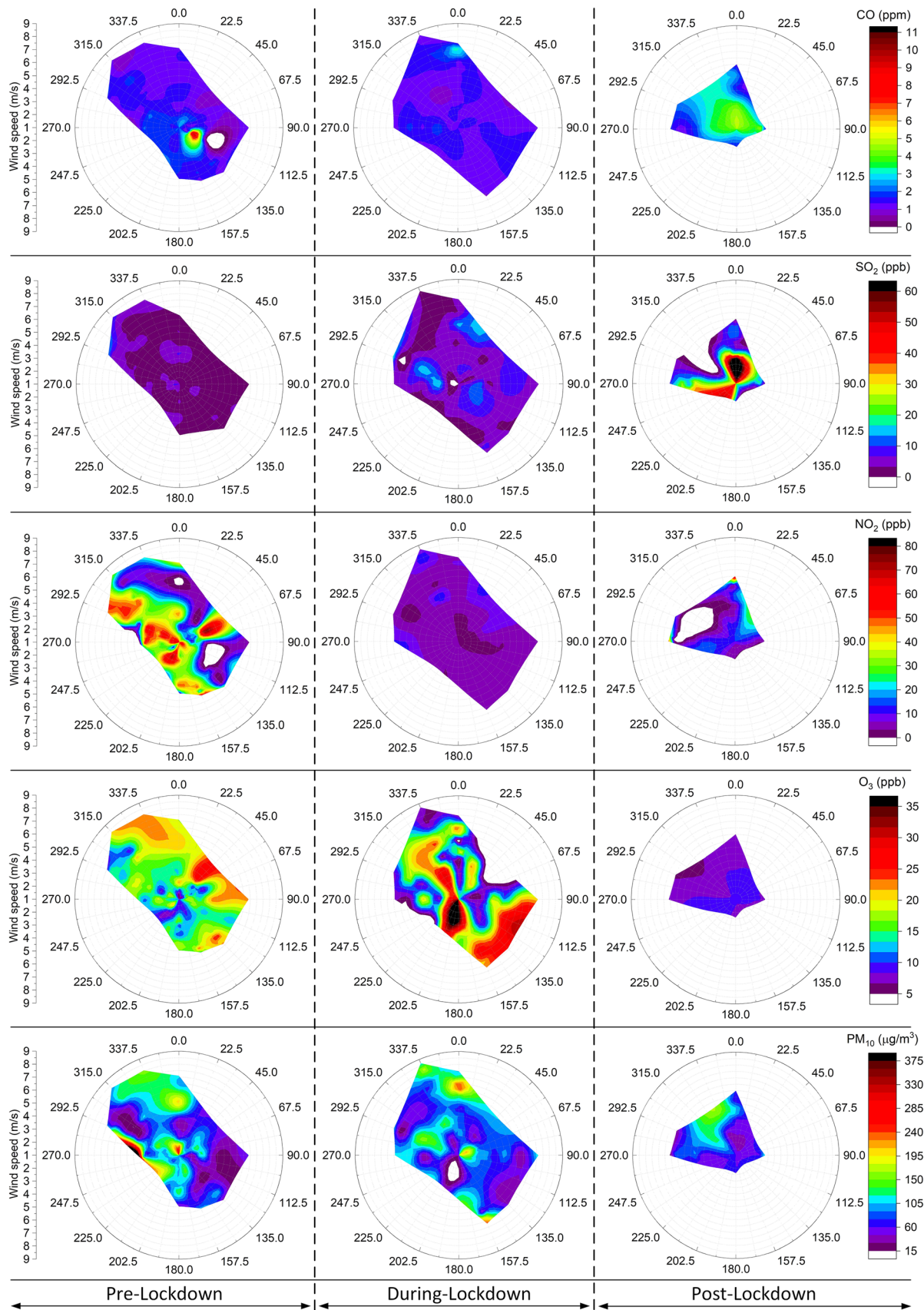


Fig. 4 Bivariate polar plots illustrating the joint effect of wind velocity and wind direction on observed pollutants at Rakah station

urban sites and then followed by Al Ahsa-Industrial (22%), Rakah-Urban (20%), and Dammam-Industrial (5.8%) sites. During the post-lockdown phase, Qatif and IAU urban stations and Al Ahsa-Industrial site indicated decreasing CO

rates of 69%, 22%, and 27%, respectively. These results reveal that the CO and NO₂ were commonly emitted from transportation activities, which were limited significantly during the lockdown and partially within post-lockdown phases,



Fig. 5 Percent changes in air pollution levels during COVID-19 pandemic compared with pre-lockdown period

especially at urban locations. On the other hand, the CO level at Jubail industrial site gradually increased by 73% and 137% during and after lockdown, respectively. These remarkable CO increase rates could be attributed to the huge and wide range of industrial activities with variable production capacities that did not respond as expected against imposed lockdown measures at the Jubail industrial city.

The ground level O₃ is classified as a secondary pollutant, and its complex formation mechanism is governed by NO_x and VOC emissions, VOC/NO_x ratio in the atmosphere, the strength of solar radiation, and atmospheric stability (Xu et al. 2020). In addition to this, the O₃ concentration at a receptor point could be under the effect of long-range transport mechanism as the atmospheric lifetime of O₃ is about 22 days (Li et al. 2020; Sicard et al. 2020). Contrary to the significant reduction rates in NO₂ during and after the lockdown, increasing O₃ rates occurred at most of the sites, ranging between 6.3 and 45% within lockdown and between 18 and 263% after lockdown. This increasing pattern might be linked to the substantially dropped NO_x emissions (reduction in titration impact on O₃), increased VOC/NO_x ratios, and stronger solar radiation as compared with before lockdown period. The highest increase rates after lifting lockdown measures were monitored at Jubail (263%) and Al Ahsa (209%) industrial sites where decreases in VOC emissions from a large number of petrochemical factories and large oil plants/refineries were not as large as NO_x emissions, most probably leading to an enhanced formation of O₃ under stronger solar radiation and more stable atmospheric conditions.

The decrease rate of SO₂ during the lockdown period was in the following order of 30% (IAU) > 25% (Qatif) > 13% (Al Ahsa-Industrial) > 10% (Dammam-Industrial) > 8.7% (Jubail). After lifting the lockdown, Jubail and IAU sites showed 45% and 18% reduction rates, respectively, while other sites indicated increasing SO₂ ratios varied between 50 and 427%. The Rakah station showed the most significant SO₂ increase rates of 82% and 427% during the lockdown and after lockdown, respectively. The highest SO₂ increase among other stations after lockdown may be ascribed to new excavation and dredging activities in the nearby residential area of the Rakah site.

Even though the Eastern Province is under the effect of a wide range of PM₁₀ emissions, the decreasing PM₁₀ trend noticed in Qatif (70%), followed by Al Ahsa-Traffic (57%), AlAhsa-Industrial (29%), and Dammam-Industrial (21%) stations is an evidence for the effect of lockdown measures. In contrary to that, the Jubail station showed the most significant increases of 196% and 378% during and after lockdown, respectively. This remarkable increase compared with other sites may be attributed to local dust storm conditions since the Jubail station is approximately 180 km and 60 km far north from Al Ahsa and Qatif/Dammam monitoring stations, respectively.

The observed reduction trends in NO₂ (all sites), CO (Qatif-Urban, IAU-Urban, and Al Ahsa-Industrial), SO₂ (Jubail-Industrial and IAU-Urban), and PM₁₀ (Al Ahsa-Traffic and Rakah-Urban) pollutants even after releasing the lockdown measures could possibly be attributed to the multiple factors: (i) preference of people staying home due to the fear of the pandemic, (ii) allowing employees work from home by most of the companies, (iii) partial or full halt of production in some factories because of shattered supply chains, and (iv) different meteorological conditions and atmospheric stabilities compared with post-lockdown period.

Comparison with other regions

The variations of pollutant concentrations due to COVID-19 lockdown in different countries around the world are shown in Table 1. The median values of percent changes in each pollutant monitored at the Eastern Province demonstrated in Table 1 are in a good agreement with those reported for the compared sites. The CO concentrations showed decreasing rates for all monitoring stations around the world. The major change in CO was observed for Almaty (Kazakhstan) from March 19 to April 14, with a percentage reduction of 49%. The same trend was observed in this study, where the median reduction value of CO was 13% during March 23 and June 21. The same similar trend was observed for NO₂. All monitoring stations showed significant decreases during lockdown compared with the pre-lockdown period. The highest NO₂ reduction was reported to be 96% for Salé (Morocco) from March 21 to April 2. On the other hand, O₃ showed an increasing concentration trend in all compared sites around the world, including our study, except for the Anqing, Hefei, and Suzhou areas of China, which indicated a reduction of 9.6%. The changes in SO₂ concentrations fluctuated between -53% (China) and 8% (São Paulo, Brazil), while PM₁₀ concentration changes varied between -75% (Salé, Morocco) and 19% (Rome, Italy). Besides, SO₂ and PM₁₀ pollutants demonstrated decreasing trends at 75% of the locations compared in Table 1.

Conclusions

In this work, the possible effects of the lockdown due to the COVID-19 pandemic on the air quality were investigated in an arid region using meteorological and air quality datasets obtained from eight monitoring stations covering the Eastern Province of the KSA within the period between September 15, 2019, and July 18, 2020. The mean concentrations of NO₂ and PM₁₀ pollutants at several monitoring stations reduced to such levels lower than the guideline values of WHO by virtue of the imposed lockdown, which might reduce the impact of COVID-19, especially on elderly and sensitive groups. The

Table 1 Variations of pollutant concentration due to COVID-19 control measures in different locations

Location	Studied lockdown period	Change of pollutant concentration due to COVID-19 control measures (%)					Reference
		CO	SO ₂	NO ₂	O ₃	PM ₁₀	
Tehran (Iran)	Mar. 21–Apr. 21	–41	–28	–33	103	–30	(Broomandi et al. 2020)
Delhi (India)	Mar. 24–Apr. 11	–30	–18	–53	0.8	–52	(Mahato et al. 2020)
Almaty (Kazakhstan)	Mar. 19–Apr. 14	–49	7	–35	15	n.a.	(Kerimray et al. 2020)
Salé (Morocco)	Mar. 21–Apr. 2	n.a.	–49	–96	n.a.	–75	(Otmami et al. 2020)
Barcelona (Spain)	Mar. 14–Mar. 30	n.a.	1.8	–51	58	–31	(Tobías et al. 2020)
São Paulo (Brazil)	Mar. 24–Apr. 20	–30	8	–22	11	7.7	(Nakada and Urban 2020)
Nice (France)	Mar.–Apr.	n.a.	n.a.	–63	24	–7.8	(Sicard et al. 2020)
Rome (Italy)		n.a.	n.a.	–46	14	19	
Turin (Italy)		n.a.	n.a.	–30	27	9.9	
Valencia (Spain)		n.a.	n.a.	–70	2.4	15	
Wuhan (China)		n.a.	n.a.	–57	36	–32	
Wuhan (China)	Jan. 23–Feb. 23	–23	–3.9	–53	117	–40	(Lian et al. 2020)
Hangzhou (China)	Jan. 24–Feb. 15	–22	–29	–58	145	–48	(Wang et al. 2020)
Yangtze River Delta Region (China)	Jan. 24–Feb. 25	–39	–26	–47	8.3	–61	(Li et al. 2020)
	Feb. 26–Mar. 31	–25	–15	–29	2.3	–36	
Anqing, Hefei, and Suzhou area (China)	Feb. 1–Feb. 29	–36	–53	–53	3.6	–49	(Xu et al. 2020)
	Mar. 1–Mar. 31	–24	–41	–27	–9.6	–25	
Eastern Region (Saudi Arabia)	Mar. 23–Jun. 20	–13 (± 36)	–9.2 (± 54)	–58 (± 26)	17 (± 38)	–21 (± 83)	This study

NO₂ was found to be the marker pollutant responding best to the lockdown measures since the concentration reductions of NO₂ during- and post-lockdown periods at all sites ranged between 12–86% and 14–81%, respectively. In parallel to decreases in the NO₂ concentrations, drops in CO concentrations fluctuated between 5.8 and 55% considering most of the sites, suggesting that CO and NO₂ emissions were mainly from transportation activities, which were substantially restricted during the lockdown phase. Interestingly, O₃ concentrations increased at the majority of the monitoring stations, ranging between 6.3 and 45% within lockdown and between 18 and 263% after lockdown. The results also revealed that controlling the formation of ground-level O₃ is a quite challenging task even by reducing the emissions of primary air pollutants significantly. The Eastern Province is a low-SO₂-emitting region due to the stringent air pollution control regulations, and the monitored SO₂ emissions have been quite below the national standards and WHO's guidelines. For this

reason, the reductions in SO₂ concentrations were not distinct and varied between 8.7 and 30% during the lockdown period. The effect of lockdown measures was also evident in PM₁₀ concentrations, which reduced within the range between 21 and 70% at most of the sites even though a wide range of emission sources dominates the PM₁₀ budget over the Eastern Province's atmosphere. Besides the damaging effects of COVID-19 pandemic, the imposed lockdown countermeasures have been a unique opportunity to investigate the effects of reduced emission rates of pollutants from various sources on the air quality, to evaluate the existing and future air quality control regulations, and to build short- and long-term alternative action plans to enhance the air quality.

Funding The authors acknowledge the funding provided by the Deanship of Scientific Research (DSR) at Imam Abdulrahman Bin Faisal University (IAU) in Saudi Arabia through research project No. 2018-044-Eng.

Compliance with ethical standards

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

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