Special Issue on COVID-19 Aerosol Drivers, Impacts and Mitigation (IV)

Aerosol and Air Quality Research, 20: 1793–1804, 2020
ISSN: 1680-8584 print / 2071-1409 online
Publisher: Taiwan Association for Aerosol Research
https://doi.org/10.4209/aaqr.2020.05.0205

Impact of COVID-19 Event on the Air Quality in Iran

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ABSTRACT

The first novel coronavirus case was confirmed in Iran in mid-February 2020. This followed by the enforcement of lockdown to tackle this contagious disease. This study aims to examine the potential effects of the COVID-19 lockdown on air quality in Iran. From 21st March to 21st April in 2019 and 2020, The Data were gathered from 12 air quality stations to analyse six criteria pollutants, namely O_3, NO_2, SO_2, CO, PM_{10}, and $PM_{2.5}$. Due to the lack of ground-level measurements, using satellite data equipped us to assess changes in air quality during the study on Iranian megacities, especially in Tehran, i.e., the capital of Iran. In this city, concentrations of primary pollutants (SO_2 5–28%, NO_2 1–33%, CO 5–41%, PM_{10} 1.4–30%) decreased with spatial variations. Although, still SO_2, NO_2, and PM_{10} exceeded the WHO daily limit levels for 31 days, 31 days, and four days, respectively. Conversely, O_3 and $PM_{2.5}$ increased by 0.5–103% and 2–50%. In terms of the national air quality, SO_2 and NO_2 levels decreased while AOD increased during the lockdown. Unfavourable meteorological conditions hindered pollutant dispersion. Moreover, reductions in the height of planetary boundary layer and rainfall were observed during the lockdown period. Despite the adverse weather conditions, a decrease in primary pollutant levels, confirms the possible improvements on the air quality in Iran.

Keywords: SARS-CoV-2; Atmospheric pollution; Lockdown; Tehran; Nitrogen dioxide; Carbon monoxide.

INTRODUCTION

As a result of the unprecedented global COVID-19 outbreak, there has been an undesirable public health emergency in our lives, causing enormous adverse economic and social repercussion. However, all these changes have also resulted in some positive outcome. One of the most significant positive results of shutting down factories, transport networks and businesses is that air pollution levels have dropped sharply.

The earliest substantial reduction in NO_2 was reported following the lockdown in Wuhan China (Dutheil *et al.*, 2020; NASA, 2020; Wang and Su, 2020). NO_2 emission cut down about 30% in Central China. CO_2 levels followed a similar reduction by 25% in China and 6% worldwide.

The COVID-19 lockdown in Almaty, Kazakhstan resulted in reductions by (29%) $PM_{2.5}$ concentration (44 ± 13–31 ± 10 µg m^{-3}), (49%) CO concentration (674 ± 255–343 ± 158 µg m^{-3}) and (35%) NO_2 concentration (37 ± 13–24 ± 12 µg m^{-3}) (Kerimray *et al.*, 2020). A similar decline has been observed in Rio de Janeiro, Brazil, in comparison to 2019 as well as weeks prior the outbreak in the levels of CO, NO_2, and PM_{10} (Dantas *et al.*, 2020).

The highest reduction met by CO level (30.3–48.5%) related to light-duty vehicular emissions comparing to the week before the outbreak. The median values of NO_2 lowered by 24.1–32.9% and CO by 37.0–43.6% comparing to the previous year, resulted in an increase of O_3 level.

In another Brazilian city, São Paulo, a remarkable reduction in CO (64.8%), NO_2 (54.3%), and NO (77.3%) were observed during lockdown compared to the five-year monthly mean. Then, O_3 increased by 30%, which is attributed to vehicular traffic (cf. Table 1 in Nakada and Urban, 2020) (Nakada and Urban, 2020). Sharma *et al.* (2020) showed an overall reduction in $PM_{2.5}$ (43%), PM_{10} (31%), CO (10%), and NO_2 (8%) levels, comparing to the previous year in 22 cities of India; however, the concentration of Ozone increased by 17%. They also showed a reduction in the air quality index (AQI) in the range of 15%–44% (Sharma *et*

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al., 2020). The air quality in the megacity of Delhi experienced a 50% decrease in the level of PM_{10}, and $PM_{2.5}$ compared to the pre-lockdown time and about 60% and 30%, to the previous year respectively (cf. Table 4 in Mahata *et al.*, 2020). NO_2 and CO levels have decreased by 53%, and 30% during the lockdown phase. In total, roughly forty to fifty percent improvement observed in the air quality of the study only four days after lockdown (Mahato *et al.*, 2020). In northern China within 44 cities, between 1st January and 21st 2020, the concentration of SO_2, $PM_{2.5}$, PM_{10}, NO_2, and CO reduced by 6.76%, 5.93%, 13.66%, 24.67%, and 4.58% respectively, and the average air quality index (AQI) decreased by 7.8% (cf. the Table 1 in Bao and Zhang, 2020). Abdullah *et al.* (2020) similar study in Malaysia reported up to 58.5% reduction in $PM_{2.5}$ levels at Politeknik Kota Kinabalu station from 41.2 to 17.1 $\mu g\ m^{-3}$ during the movement control order (cf. Table 4 in Abdullah *et al.*, 2020).

In mid-February 2020, the first case of coronavirus infections (COVID-19) was reported in Qom, Iran. By a rapid increase in infection rate, the outbreak became a national crisis. Iranian authorities decided to battle against contagious disease by reducing transportation between and within megacities, especially to Tehran, the closure of educational institutions, business centres, holy places and social venues, to prevent the coronavirus from taking more lives.

Tehran metropolitan is located in the northern part of the country, with a population of around 8.5 million. In the daytime, its population exceeds 12.5 million, due to the commute from nearby towns (Shahbazi *et al.*, 2016, 2018). There are more than 17 million daily vehicular trips (with outdated technology) within Tehran (Shahbazi *et al.*, 2016; Alipourmohajer *et al.*, 2019).

The megacity of Tehran ranks 12th among 26 megacities in terms of PM_{10} levels (Heger and Sarraf, 2018). In 2016, the annual value of PM_{10} was estimated at (77 $\mu g\ m^{-3}$), which is almost four times of WHO's limit value (20 $\mu g\ m^{-3}$) (Heger and Sarraf, 2018). Tehran is at a high elevation, surrounded by the Alborz Mountain Range which is trapping polluted air. Temperature inversion prevents the pollutants from being diluted during winter months. Industrial developments, rapid population growth, fuel consumption increases, and urbanisation are pressure points for clean air in Tehran (Heger and Sarraf, 2018). A mixture of sources is responsible for releasing pollutants in Tehran. Like other megacities, vehicular traffic plays a crucial role in air quality. However, the exponential growth in the vehicular fleet, along with fast population growth, have been undergone (Azarmi and Arhami, 2017).

In Tehran, there are total 4.24 million vehicles which consist of 80 percent of passenger cars, 18 percent motorcyclists, 2 percent High Duty Vehicles (HDVs) amounting to 3.37, 0.76, 0.1 million vehicles respectively. On-road vehicles are responsible for nitrogen oxides (NO_x), $PM_{2.5}$, PM_{10}, and CO emissions (Azarmi and Arhami, 2017). Based on previous studies, mobile sources generate about 80% of these pollutants (Halek *et al.*, 2010; Azarmi and Arhami, 2017).

The stationary sources such as the industrial sector also released CO, SO_2, NO_x, and PM_{10} into the air by fossil fuel combustion (mainly diesel and natural gas) (Halek *et al.*, 2004). Energy demand in Tehran amounts to twenty percent of whole country energy consumption.

The secondary pollutants such as Ozone and ultrafine aerosols are also added to the air by the photochemical reaction of inorganic gases and precursor of organic vapours released from the mentioned sources (Azarmi and Arhami, 2017).

Until 2007, CO was the most notable issue in the air pollution which triggered Tehran to decrease exceeding CO level to safety standard with various countermeasures, including forcing industries to relocate outside the city perimeter and the phasing out of a fraction of old, highly polluting vehicles (Azarmi and Arhami, 2017). In 2010, $PM_{2.5}$ measurement method was employed, and since then, it has become the major air pollutant element, resulting in an apparent increase in polluted days.

Air pollution costs Iran several billion dollars each year (Azarmi and Arhami, 2017; Heger and Sarraf, 2018). Only in 2007, 3600 people died in a single month as a result of air pollution in Tehran (Miri *et al.*, 2017; Hopke *et al.*, 2018; Yarahmadi *et al.*, 2018; Hadei *et al.*, 2020). Exposure to nitrogen dioxide (NO_2), sulfur dioxide (SO_2), and Ozone (O_3) has resulted in excessive mortality rate per year in Tehran, approximately 1050, 1460, and 820, respectively (Azarmi and Arhami, 2017). This study aims to evaluate the plausible reductions in air pollutants during the movement restriction in Iran with a particular focus on Tehran. The criteria pollutants, O_3, NO_2, SO_2, CO, PM_{10}, and $PM_{2.5}$ in 12 air quality stations in Tehran and satellite data for other Iranian megacities, were used to assess the changes of air quality from 21st March to 21st April in 2019 and 2020.

MATERIALS AND METHODS:

Site Description

The lockdown in Iran started on 21st March 2020 and eased on 21st April 2020; therefore, we decided to study the changing trend in air quality a month prior and during the lockdown and compare it with the same time frame in 2019 to show the fluctuations in air pollution. Air quality data, i.e., hourly concentrations of SO_2, NO_2, CO, PM_{10}, and $PM_{2.5}$, were obtained from Tehran Air Quality Control Company monitoring stations network (TAQCC) (https://aqms.doe.ir/Data/Index) and from Department of Environment (DoE) in Iran for other seven megacities including Shiraz, Esfahan, Karaj, Arak, Tabriz, Ahvaz, and Mashhad (JICA, 2005; Data, 2016) for the period of 20th February to 21st April in 2019 and 2020.

The pollution data are validated for each monitoring station during the study period. The zero or negative values were removed from the dataset. Then, the stations with more than 75% available data (hourly concentrations) were considered valid (Shafiee *et al.*, 2016a, b). Only 12 stations in Tehran were passed the validation criteria, namely Aghdasieh (35°79'N and 51°48'E), District-2 (35°77'N and 51°36'E), District-19 (35°63'N and 51°36'E), District-21 (35°69'N and 51°24'E), Fath-Square (35°67'N and 51°33'E), Mahhalati (35°66'N and 51°46'E), Punak (35°76'N and

51°33'E), Ray (35°60'N and 51°42'E), Sadr (35°77'N and 51°42'E), Shad Abad (35°67'N and 51°29'E), Tarbiat Modaress University (35°71'N and 51°38'E), Sharif University (35°70'N and 51°35'E). Due to the low data coverage, lack of pollutant measurement, satellite images were used to study the air quality in other cities.

Satellite Data

Level-3 Aura/OMI Global OMSO2e Data Products (Sulfur Dioxide (SO_2) Total Column) with a resolution of 0.25 × 0.25 degree, Level-3 Aura/OMI Global OMNO2d Data Products (Nitrogen Dioxide (NO_2) Cloud-Screened Total and Tropospheric Column) with a resolution of 0.25 × 0.25 degree, and daily NASA MODIS/AQUA Atmosphere Level 2 Aerosol Product (MYD 04) (deep blue Aerosol Optical Depth (AOD) at the spatial resolution of a 10 × 10 km were used to assess air quality changes during studied time frames over Iranian megacities.

Reanalysis for Climate Monitoring

ERA5 reanalysis data, produced by C3S at ECMWF, as the current atmospheric reanalysis and based on a 2016 version of the Integrated Forecasting System (IFS), was employed to evaluate climate changes in studied time frames.

RESULT AND DISCUSSION

Impacts on the Air Quality of Tehran City

Tables 1 and 2 report the average concentrations of SO_2, NO_2, O_3, PM_{10}, $PM_{2.5}$, and CO, from 21st March to 21st April in 2019 and 2020 in Tehran. Figs. 1–3 show the concentrations changes; SO_2, NO_2, CO, and PM_{10} levels reduced with spatial variation of 5–28%, 1–33%, 5–41%, and 1.4–30% while O_3 and $PM_{2.5}$ had increases of 0.5–103% and 2–50%, respectively. District-19, Aghdashieh, Shad Abad, and Mahallati stations experienced the most significant reductions of CO (from 1.69 ± 0.54 to 1 ± 0 µg m^{-3}), NO_2 (from 47.96 ± 15.62 to 32.06 ± 7.99 ppb), SO_2 (from 5.52 ± 2.25 to 4 ± 0.97pbb), and PM_{10} (from 49.45 ± 21.81 to 34.67 ± 11.50 µg m^{-3}). Despite the decreases, still, NO_2, SO_2, and PM_{10} level exceed the WHO daily limit levels for 31 days, 31 days, and four days, respectively. During the lockdown period, District-2 station recorded the highest increases of O_3 (from 16.66 ± 6.39 to 33.91 ± 8.65 ppb) and $PM_{2.5}$ (from 10.27 ± 3.69 to 15.36 ± 5.72 µg m^{-3}).

Similar studies conducted over East China using the satellite-derived mean columns showed the significant reduction of NO_2 (30%) and CO (20%) in their concentrations due to the decrease in urban transport and economic growth during lockdown period (Filonchyk *et al.*, 2020). Another

Tables 1. The average concentrations of SO_2, NO_2, O_3, PM_{10}, $PM_{2.5}$, and CO for the period of 21st March to 21st April in 2019 in Tehran.

	O_3 (ppb)	CO (ppm)	NO_2 (ppb)	SO_2 (ppb)	PM_{10} (µg m^{-3})	$PM_{2.5}$ (µg m^{-3})
Aghdasieh	25.24 ± 6.85	1.21 ± 0.42	47.96 ± 15.62	NAN	24.15 ± 12.97	NAN
District-2	16.66 ± 6.39	1.13 ± 0.35	NAN	NAN	30.55 ± 13.62	10.27 ± 3.69
District-19	25.06 ± 8.74	1.69 ± 0.54	NAN	3.53 ± 1.77	59.09 ± 30.53	NAN
District-21	25.33 ± 6.87	NAN	37.48 ± 7.80	4.19 ± 1.42	46.24 ± 21.43	19.88 ± 5.03
Fath-Square	23.82 ± 6.70	1.38 ± 0.55	40.36 ± 7.44	3.91 ± 1.53	58.30 ± 26.65	NAN
Mahhalati	20.82 ± 4.99	1.03 ± 0.18	34.09 ± 5.66	3.33 ± 1.45	49.45 ± 21.81	NAN
Punak	22.09 ± 9.54	1.42 ± 0.71	39.69 ± 9.36	2.09 ± 0.91	30.12 ± 13.16	10.97 ± 4.08
Ray	17.97 ± 4.76	NAN	43.17 ± 7.52	NAN	48.03 ± 23.34	18.58 ± 6.29
Sadr	27.67 ± 6.15	2.09 ± 0.63	48.39 ± 10.08	4 ± 1.25	NAN	20.03 ± 6.76
Shad Abad	27.97 ± 7.24	1.09 ± 0.29	37.64 ± 6.96	5.52 ± 2.25	48.39 ± 19.85	17.18 ± 4.83
Tarbiat Modaress University	28.79 ± 7.81	1.21 ± 0.48	42.30 ± 7.80	2.82 ± 1.04	39.18 ± 17.54	15.03 ± 5.70
Sharif University	19.50 ± 6.30	1.27 ± 0.45	41.76 ± 7.50	3.97 ± 1.36	36.24 ± 16.53	19.91 ± 5.24

Tables 2. The average concentrations of SO_2, NO_2, O_3, PM_{10}, $PM_{2.5}$, and CO for the period of 21st March to 21st April in 2020 in Tehran.

	O_3 (ppb)	CO (ppm)	NO_2 (ppb)	SO_2 (ppb)	PM_{10} (µg m^{-3})	$PM_{2.5}$(µg m^{-3})
Aghdasieh	27.52 ± 9.94	1.06 ± 0.24	32.06 ± 7.99	NAN	24.18 ± 10.73	NAN
District-2	33.91 ± 8.65	1.21 ± 0.42	NAN	NAN	34.33 ± 10.69	15.36 ± 5.72
District-19	22.36 ± 5.88	1 ± 0	NAN	3.64 ± 1.19	51.88 ± 18.08	NAN
District-21	25.15 ± 6.45	NAN	35.76 ± 9.94	4 ± 0.87	42.21 ± 14.88	20.24 ± 5.68
Fath-Square	14.27 ± 3.07	1.42 ± 0.66	39.97 ± 12.35	3.97 ± 1.87	43.27 ± 15.84	NAN
Mahhalati	26.18 ± 7.71	1 ± 0	32.18 ± 6.62	3.67 ± 1.05	34.67 ± 11.50	NAN
Punak	25.39 ± 7.99	1.21 ± 0.42	34.67 ± 7.82	1.79 ± 0.82	32.24 ± 11.02	10.94 ± 3.33
Ray	18.07 ± 4.46	NAN	34.41 ± 8.32	NAN	39.44 ± 16.27	17.74 ± 6.13
Sadr	25.12 ± 7.64	1.67 ± 0.60	42.30 ± 11.35	3.27 ± 1.18	NAN	22.06 ± 8.90
Shad Abad	28.10 ± 6.76	1.03 ± 0.1	33.45 ± 9.48	4 ± 0.97	44.90 ± 14.13	20.36 ± 6.36
Tarbiat Modaress University	16.27 ± 3.53	1.30 ± 0.47	34.67 ± 8.35	3 ± 1.03	36.52 ± 13.91	19.91 ± 7.16
Sharif University	25.12 ± 6.65	1.33 ± 0.48	36.79 ± 11.12	4.06 ± 0.86	35.73 ± 12.10	19.18 ± 6.61

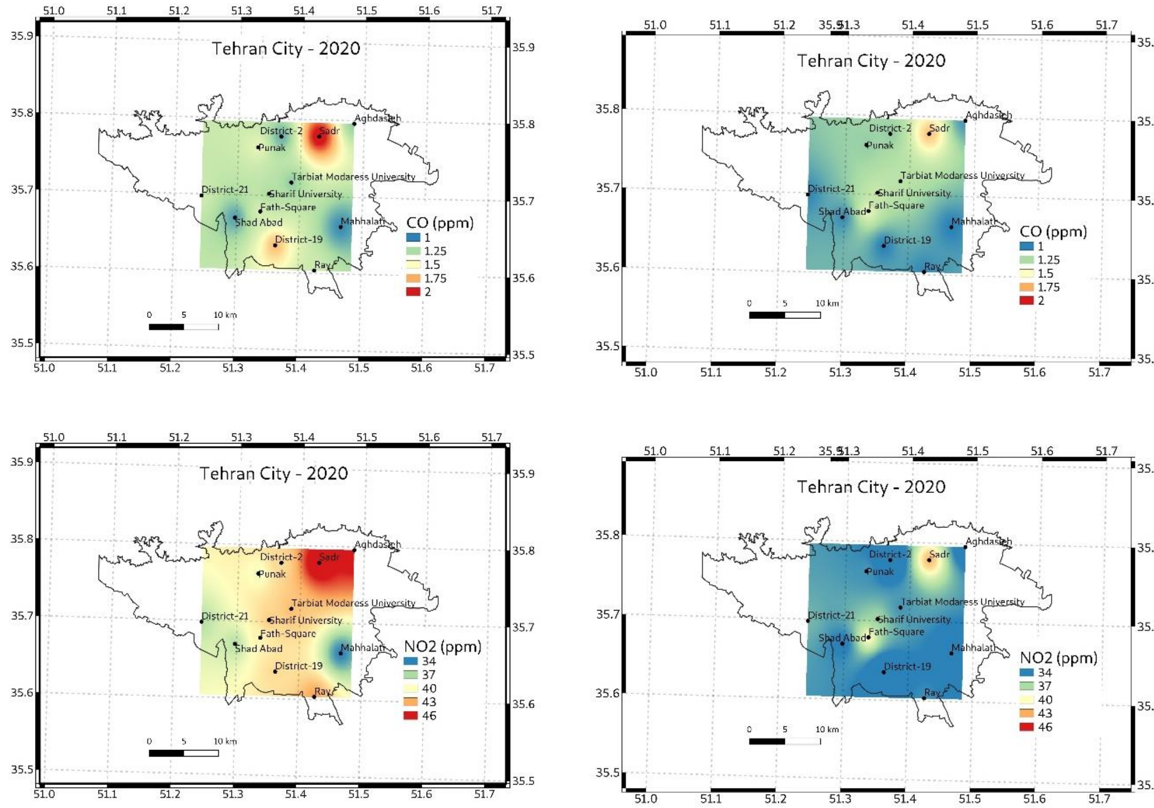

Fig. 1. The average concentration of CO (ppm) and NO_2 (ppb) in studied stations of Tehran megacity, Iran, for the period of 21st March to 21st April in 2019 and 2020.

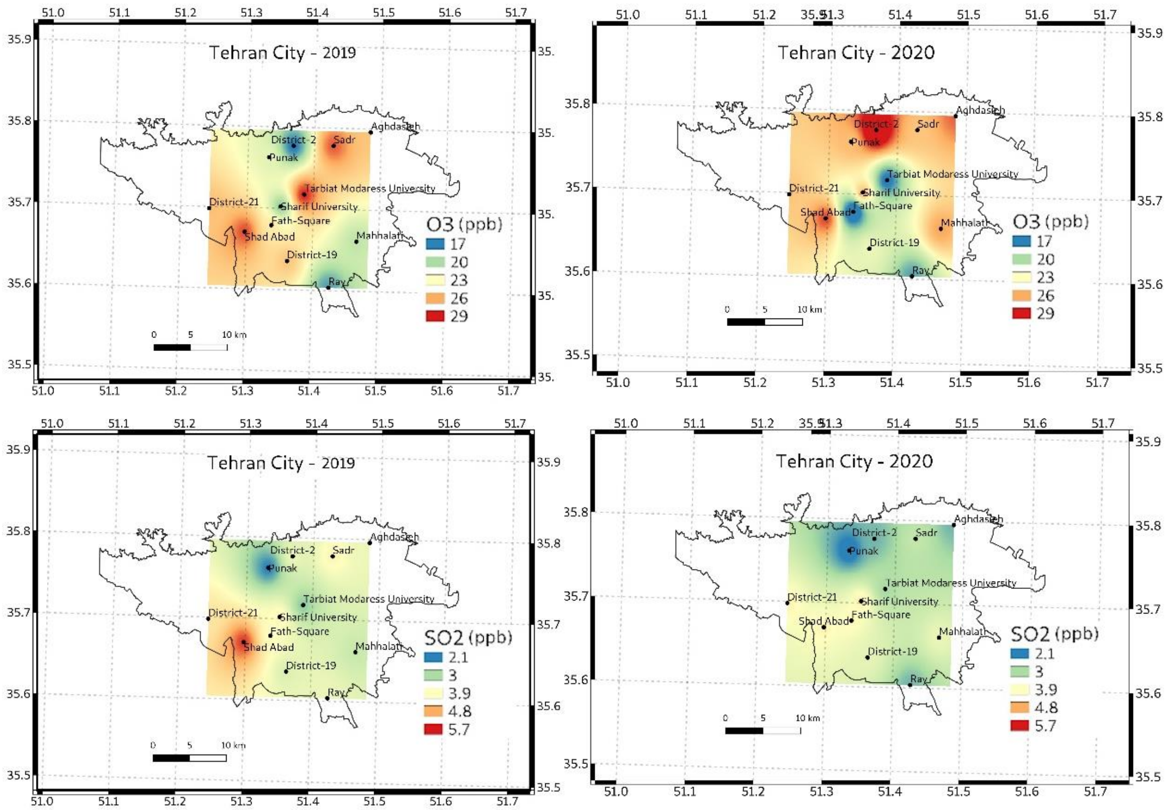

Fig. 2. The average concentration of SO_2 (ppb) and O_3 (ppb) in studied stations of Tehran megacity, Iran, for the period of 21st March to 21st April in 2019 and 2020.

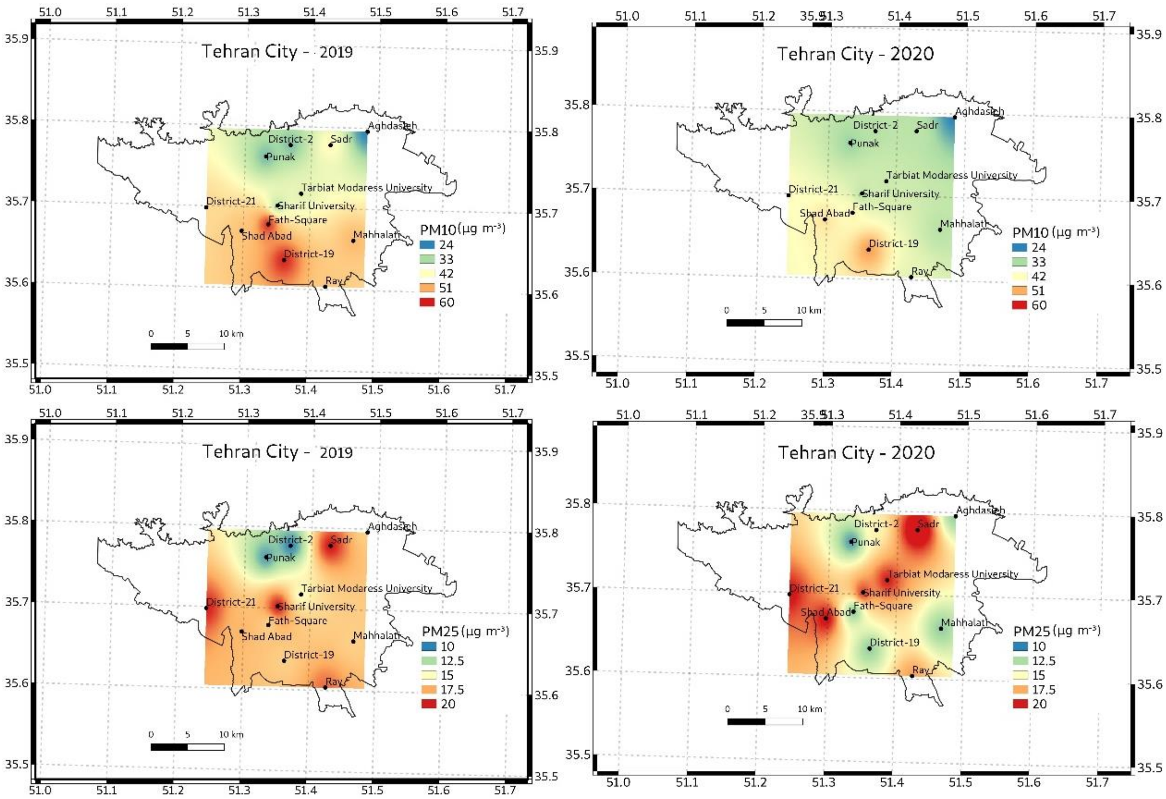

Fig. 3. The average concentration of PM_{10} ($\mu g\ m^{-3}$) and $PM_{2.5}$ ($\mu g\ m^{-3}$) in studied stations of Tehran megacity, Iran, for the period of 21st March to 21st April in 2019 and 2020.

research studied the air quality in three cities of Anqing, Hefei, Suzhou in Anhui Province, near central China (Xu *et al.*, 2020a). recorded total reduction of 46.5%, 48.9%, 52.5%, 36.2%, and 52.8% for $PM_{2.5}$, PM_{10}, SO_2, CO, and NO_2, respectively during February 2020 (Xu *et al.*, 2020a) (Table 3). Conducted study in Wuhan, Jingmen, and Enshi (central China), reported total reductions of $PM_{2.5}$ (30.1%), PM_{10} (40.5%), SO_2 (33.4%), CO (27.9%), and NO_2 (61.4%) during the pandemic (Xu *et al.*, 2020b) (Table 3). In Beijing Tianjin-Hebei region (in mainland China), a reduction in $PM_{2.5}$, PM_{10}, SO_2, NO_2 and CO concentrations from 100 $\mu g\ m^{-3}$, 150 $\mu g\ m^{-3}$, 20 $\mu g\ m^{-3}$, 40 $\mu g\ m^{-3}$, and 1.2 $mg\ m^{-3}$ in February 2019 to 70 $\mu g\ m^{-3}$, 80 $\mu g\ m^{-3}$, 10 $\mu g\ m^{-3}$, 25 $\mu g\ m^{-3}$, and 0.5 $mg\ m^{-3}$ in February 2020, respectively (Chen *et al.*, 2020).

In Malaysia (an Urban Area of Klang Valley), a study showed a reduction of 58.9%, 51.8%, and 47.5% in the level of $PM_{2.5}$, PM_{10}, and CO during lockdown comparing to normal days. The highest recorded reduction of $PM_{2.5}$ (from 1540 to 477 $\mu g\ m^{-3}$) and PM_{10} (from 7110 to 2540 $\mu g\ m^{-3}$) were observed in the BG (Bukit Gasing) site (Mohd Nadzir *et al.*, 2020). While CO had its highest reduction from 8.59 ppm to 6.24 ppm (by percent of 47.5%) in Uptown (UP) station. On the other hand, they reported an increase in $PM_{2.5}$ by (60%) and PM_{10} by (9.7%) levels in Kota Damansara (KD) site, during lockdown days probably caused by Local burning activities in the residential area of Kota Damansara (KD) site (Mohd Nadzir *et al.*, 2020). In Delhi, India a statistically significant reduction was observed in the concentration of PM_{10}, $PM_{2.5}$, CO, and NO_2 by the percent of~52% (153–73 $\mu g\ m^{-3}$), ~41% (66–39 $\mu g\ m^{-3}$), ~28% (0.9–0.65 $mg\ m^{-3}$), and ~51% (39–19 $\mu g\ m^{-3}$) and during the lockdown, respectively (Jain and Sharma, 2020).

In our study, During the lockdown period, District-2 station recorded the highest increases of O_3 (from 16.66 ± 6.39 to 33.91 ± 8.65 ppb) in Tehran megacity. The same results were obtained in similar studies. Xu *et al.* (2020a) witnessed the O_3 increase in cities of Anqing and Hefei (near central China) 8.2% and 3.3%, while reported a reduction in Suzhou by 0.06%. But the average Ozone increased by 3.6% in February 2020 compared with its mean value in February 2017–2019 (Table 3). Conducted study in central China (cities of Wuhan, Jingmen, and Enshi) reported an increase in ozone concentration by 27.1%, 8.9%, and 6.9%, respectively (Xu *et al.*, 2020b). The average O_3 rose by 14.3% during February 2020 compared with that in February 2017–2019 (Xu *et al.*, 2020b) (Table 3). In mainland China, an increase of Ozone was shown in 28 provinces. Five of them had the highest rate of increase over 20% including Hubei (22%) Guangxi (23%), Guangdong (23%), Jiangxi (30%), and Hainan (34%), where the ozone concentrations rose from 48 $\mu g\ m^{-3}$, 40 $\mu g\ m^{-3}$, 48 $\mu g\ m^{-3}$, 55 $\mu g\ m^{-3}$, and 48 $\mu g\ m^{-3}$ in February–April 2019 to 66 $\mu g\ m^{-3}$, 48 $\mu g\ m^{-3}$, 59 $\mu g\ m^{-3}$, 65 $\mu g\ m^{-3}$, and 64 $\mu g\ m^{-3}$ in February–April 2020, respectively (Chen *et al.*, 2020).

The opposing trend of Ozone due to favourable conditions for photochemical reactions attributed to the reduction in NO_2 and increase in solar insolation leading to changes in

Table 3. The comparison among reduction (%) caused by COVID-19 lockdown in some selected studies.

City	O_3 (ppb)	CO (ppm)	NO_2 (ppb)	SO_2 (ppb)	PM_{10} (µg m^{-3})	$PM_{2.5}$ (µg m^{-3})	Reference
Tehran	+3%	−13%	−13%	−12.5%	−11.33%	+10.50%	Current study
Almaty	+15% (30.0–34.0)	−49% (674.0–343.0)	−35% (37.0–24.0)	+7% (49.0–52.0)	---	−29% (44.0–31.0)	(Kerimray *et al.*, 2020)
São Paulo	+30%	−64.8%	-54.3%	---	---	---	(Nakada and Urban, 2020)
Delhi	---	-30%	-53%	---	-60%	-30%	(Mahato *et al.*, 2020)
Anqing	+8.2% (37.9–41.0)	−19.7% (0.76–0.61)	-36.5% (21.2–13.5)	-48.5% (5.02–2.59)	-47.2% (100.4–58.9)	-29.7% (53.0–37.3)	(Xu *et al.*, 2020a)
Hefei	+3.3% (33.7–34.8)	−24.5% (0.92–0.69)	-21.7% (26.4–20.7)	-47.6% (3.81–2.00)	-35.7% (92.2–59.3)	-35.8% (54.4–34.9)	(Xu *et al.*, 2020a)
Suzhou	−0.06% (37.3–37.1)	−5.8% (0.91–0.86)	-36.5% (23.9–15.2)	-67.1% (6.72–2.21)	-19.0% (138.1–111.9)	-33.5% (68.7–45.6)	(Xu *et al.*, 2020a)
Wuhan	+27.1% (27.7 35.2)	−16.2% (0.88–0.73)	-54.7% (30.0–10.41)	-29.9% (3.79–2.66)	-47.9% (88.2–46.0)	-44.0% (67.9–38.0)	(Xu *et al.*, 2020b)
Jingmen	+8.9% (36.3–39.5)	−31.9% (0.85–0.58)	-64.3% (16.8–6.01)	-34.9% (5.47–3.56)	-48.4% (105.0–54.2)	-30.5% (82.1–57.1)	(Xu *et al.*, 2020b)
Enshi	+6.9% (21.0–22.4)	−35.8% (0.76–0.49)	-65.2% (10.6–3.68)	−35.4% (2.28–1.47)	−25.1% (69.6–52.1)	−15.7% (51.5–43.4)	(Xu *et al.*, 2020b)
Klang Valley	---	−47.5%	---	---	−51.8%	−58.9%	(Mohd Nadzir *et al.*, 2020)

the photochemical reactions determining ozone formation and destruction (Sharma *et al.*, 2020; Xu *et al.*, 2020a, b). Generally, NO_x and Ozone have a negative correlation. The underlying chemistry between ozone concentration and anthropogenic emissions like NO_x in a VOC-limited environment in company with the meteorological parameters control the accumulation of surface O_3 in the atmosphere (Gorai *et al.*, 2015; Saini *et al.*, 2017; Jain and Sharma, 2020). A lower NO_2 level results in lower NO concentration, then decreasing the possibility of NO reacting with Ozone and therefore inhibiting ozone accumulation. Previous studies showed that on-road vehicles are responsible for the emitting of nitrogen oxides (NO_x), $PM_{2.5}$, PM_{10}, and CO in Tehran (generating about 80% of these pollutants) (Halek *et al.*, 2010; Azarmi and Arhami, 2017). NO_2, CO, PM_{10}, and SO_2 decreases in Tehran, similar to the total reductions of NO_2 and SO_2 levels in Iran, are attributed to the lockdown and the drastic reduction of traffic emissions following the coronavirus' massive outbreak. Table 3 shows the comparison between our results and some selected similar studies.

Due to movement control restriction caused by COVID-19 outbreak, a notable reduction in pollutants' emissions was observed. In Tehran, in contrast with other selected cities, a significant reduction in pollutant concentration was not observed due to the coincidence with Persian New Year holiday (Nowruz) which commences on 21st March each year and last for 14 days. During the lockdown period, all educational centres and companies shut down, and on-road traffic was less than the rest of the year. As a result, the significant decline in air pollution observed in other chosen cities was not captured during lockdown comparing to the same time frame in 2019 in Tehran. The highest amount of reduction in CO (64.8%), NO_2 (65.2%), SO_2 (67.1%), PM_{10} (60%), and $PM_{2.5}$ (58.9%) happened at São Paulo (Brazil) (Nakada and Urban, 2020), Enshi (China) (Xu *et al.*, 2020b), Suzhou (China) (Xu *et al.*, 2020a), Delhi (India) (Mahato *et al.*, 2020), and Klang Valley (Malaysia) (Mohd Nadzir *et al.*, 2020), respectively (Table 3).

In Tehran, Heavy-Duty Vehicles (HDVs), powered by diesel engines, make the highest contribution of eighty-five percent in mobile PM emissions (Shahbazi *et al.*, 2016). Fuel quality is one of the most critical emission factors for fuel combustion and evaporation (Ghadiri *et al.*, 2017), and in most cases, diesel fuel quality does not comply with the Euro 4 standards in Iran (CAQC, 2013). Beside fuel type, age, and outdated vehicular technology are the other critical factors for high levels of PM emissions (Shahbazi *et al.*, 2016). Therefore, it is recommended to apply scrappage and replacement programs for older HDVs, ensuring enforcement and compliance with latest fuel standards, improvement of vehicle monitoring and inspection, and incentivising hybrid and electric vehicles, including motorcycles, cars, and HDVs (Heger and Sarraf, 2018). Cars are the most common and congestion-causing vehicle type with the contribution of only about 3 percent of the city's transport-related PM pollution. Five percent of taxis, nine percent of passenger cars, and twenty-two percent of pick-ups have carburettor engines. The vehicles with old technology are responsible for releasing a significant amount of PM comparing to the newer technological alternatives; for example, the carburettor-equipped passenger cars make a contribution of 51 percent in total emission from all the passenger cars. The PM emission levels could significantly drop if these vehicles could be replaced by Euro 4 vehicles or retrofitted. Motorcycles are the most pollution-intensive vehicle per passenger due to incomplete fuel combustion, and they are responsible for about 12 percent of the total mobile PM emissions caused. The motorcycle fleet in Tehran consists mostly of carburettor-equipped motorcycles, being less fuel-efficient and producing more emissions compared to the newer ones with fuel injection technologies (Shahbazi *et al.*, 2016; Ghadiri *et al.*, 2017; Shahbazi *et al.*, 2018).

Although having significant reductions, the exceeding WHO daily limit values of NO_2, SO_2, and PM_{10} confirms that stationary sources from the industrial sector with fossil fuel combustion (mainly diesel and natural gas) play a prominent role in the complex source mix (Halek *et al.*, 2004). A similar case reported in Almaty, where the contribution of non-traffic sources was attributed to the exceeding levels during the lockdown period (Kerimray *et al.*, 2020).

Fig. 3 and Table 3 showed an increase in the averaged $PM_{2.5}$ concentration in Tehran. It is worth mentioning that in stations such as Sharif University, Punak, and Ray which are very close to residential areas and highways due to the movement control order, the $PM_{2.5}$ values showed a reduction (Arhami *et al.*, 2018). But in stations close to industrial sectors such as Shad Abad, an increase was observed, which was probably due to the increased industrial activities in the Neighbourhood comparing to the previous year at the same time frame. Also, the massive construction activities are another potential source group of PM in Tehran. For example, the large old bridge of Gisha, which is near the Tarbiat Modaress University station, was removed in 2019, and now there is a massive road construction activity in the area.

Another possible reason for the increased levels of $PM_{2.5}$ is sand and dust storms (Halek *et al.*, 2004; Heger and Sarraf, 2018). Heger and Sarraf (2018) reported that the contribution of dust and sand storms to $PM_{2.5}$ is about one-in-four levels in Tehran. Prevailing winds from the west of Tehran carry dust storms both from local areas and from even from neighbouring countries. Although the natural particle contribution is significant in Tehran, it is much less critical than other cities like Zabol (Rashki *et al.*, 2013), and Ahvaz (Broomandi *et al.*, 2017b, 2018; Gholami *et al.*, 2020), where the main origins of PM pollution are dust and sand storms.

Impacts on the National Air Quality of Iran

Fig. 4 shows that SO_2 and NO_2 levels decreased while AOD increased during the state of emergency. The overall reductions in SO_2 and NO_2 levels confirm the positive effect of the lockdowns on air quality, while the dust and storm events slightly increased AOD levels over the country during the same period. The observed lowered levels all over the country during the lockdown could not only be attributed to the reduction of the diesel vehicle emissions, but also the reductions in interstate and local bus circulation, enormous cancellation of flights, and decreasing demand for energy production.

Despite the reductions of emissions in Iran, especially for mobile sources, the event of dust storms kept increasing the PM levels during the lockdown period, since the Dust Belt stretches out from Western Sahara across Iran to Eastern and Central Asia and the dust activities prevail from March to September (Rashki *et al.*, 2013; Gholami *et al.*, 2020). Fig. 4 shows a slight increase in AOD levels in Central Iran comparing to that in 2019. Earlier studies showed an acceleration of wind erosion in Central parts of Iran in recent years. They compared to 20 years of 1965–1985, Dust storm Index (DSI) increased three times during the last 30 years of 1985–2014 (Vali and Roustaei, 2018). Based on their study, the central and southern parts of Central Iran has the highest severity of wind erosion and its severity reduced by approaching the north (Vali and Roustaei, 2018). Meteorological maps (Fig. 4) shows a reduction in rainfall, relative humidity in Central and southern parts of Central Iran in 2020 comparing to 2019. Also, an increase in temperature was observed in 2020 in Central and southern parts of Central Iran in 2020 comparing to 2019. Reduced rainfall and relative humidity and increased temperature can be plausible reasons for a slight increase of AOD over Central parts of Iran because any reduction in rainfall can cause a decrease in soil moisture content as a controlling factor of sand and dust storm occurrence (Huang and Gao, 2001; Cao *et al.*, 2015; Broomandi *et al.*, 2017a).

Effects of Meteorology

The impact of the meteorological conditions on air quality needs to be assessed since pollutant concentrations depend not only on emissions but also on weather conditions, transport, wet and dry depositions, and atmospheric chemistry. Figs. 5 and 6 presented the meteorological condition over Iran during the same time frame in 2019 and 2020. Fig. 5 shows a reduction in Planetary Boundary Layer Height (PBLH), in association with a decreased amount of precipitation in 2020 comparing to 2019 (Zhou *et al.*, 2007), which indicates an unfavourable meteorological condition to pollutant dispersion. Such kind of combinations are expected to intensify air pollution in a typical business-as-usual case, but the positive impact of the movement control order in the country seems to have better improvement in the air quality. Fig. 6 shows the similar patterns in temperature, wind speed, and wind direction in Iran, while relative humidity was reduced this year compared to 2019 (cf. overall reduction of NO_2, SO_2 in Fig. 4). Similar results reported in China with insignificant improvements in the air quality due to unfavourable meteorology (Wang and Su, 2020). However, Nakada and Urban (2020) confirmed favourable conditions to pollutant dispersion both before and during the lockdown, indicating its positive influence on the top of lockdown effect on air pollution reduction in São Paulo, Brazil (Nakada and Urban, 2020). Sharma *et al.* (2020) investigated the role of the pre-monsoon period, which is again a favourable condition in terms of pollution dispersion. They also showed that even under unfavourable simulated meteorological conditions using WRF-AERMOD, the $PM_{2.5}$ concentration would slightly increase but stay under Central Pollution Control Board

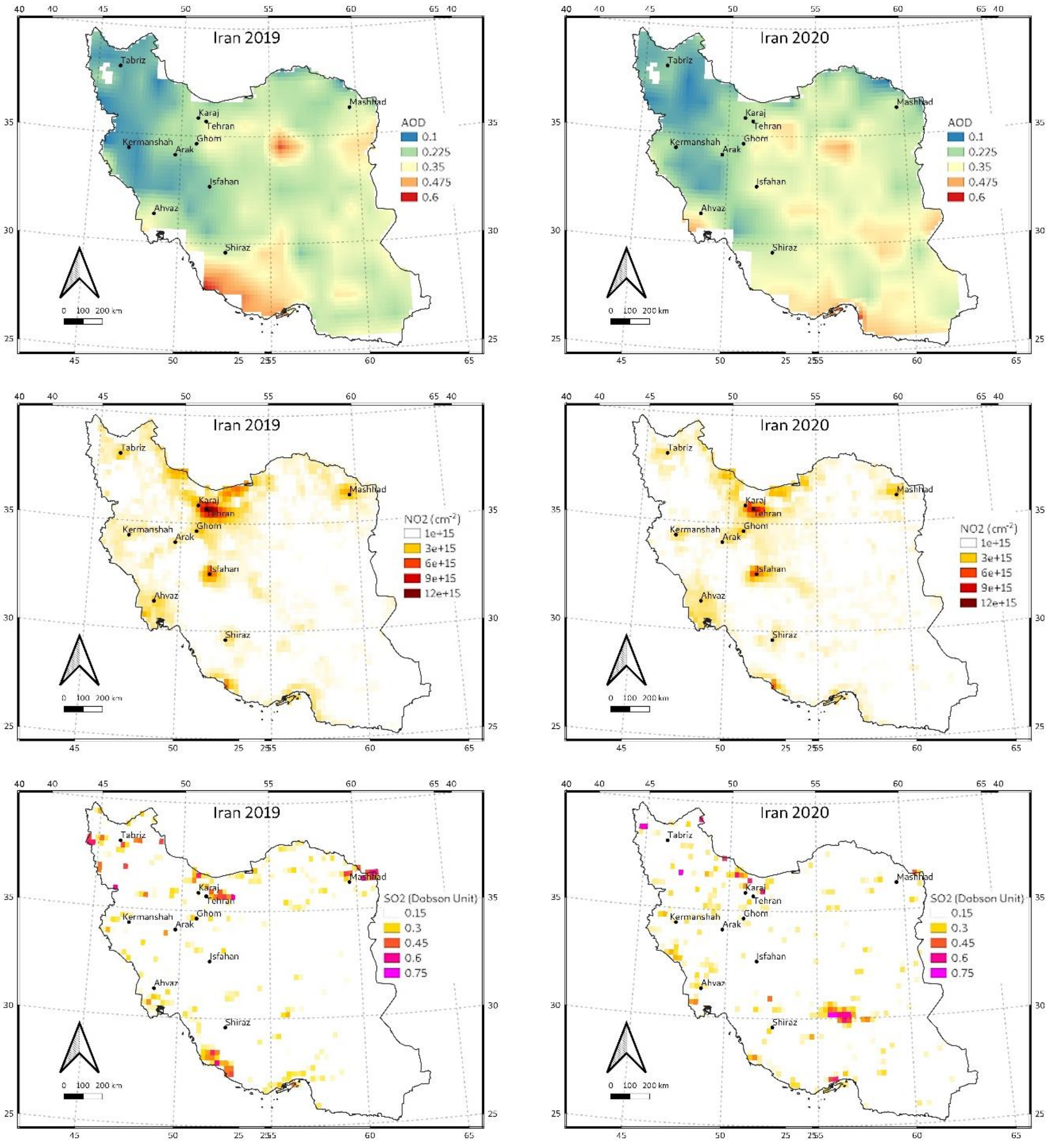

Fig. 4. The average value of NO_2, SO_2, and AOD in Iran for the period of 21st March to 21st April in 2019 and 2020.

limits during lockdown (Sharma *et al.*, 2020). Kerimray *et al.* (2020) discussed that most of the counties experienced their pandemic lockdowns during the transitional period from winter to spring, which provides more favourable conditions for air pollution reductions; however, it was different in our case study.

CONCLUSION

The current study showed the COVID-19 lockdown positively affected Iran's air quality, especially Tehran. Due to the reduced road traffic and economic activities, a reduction in the level of CO, NO_2, SO_2, PM_{10} despite the unfavourable weather conditions was observed in Tehran. In contrast, the Ozone and $PM_{2.5}$ concentrations were increased. It is necessary to mention that the effect of weather conditions on pollution levels needs further analysis in the future. The pandemic lockdown in Iran clearly showed that it is possible to have significant air pollution reduction in megacities by effective traffic control programs along with the promotions of green commuting and the technologies to expand remote working.

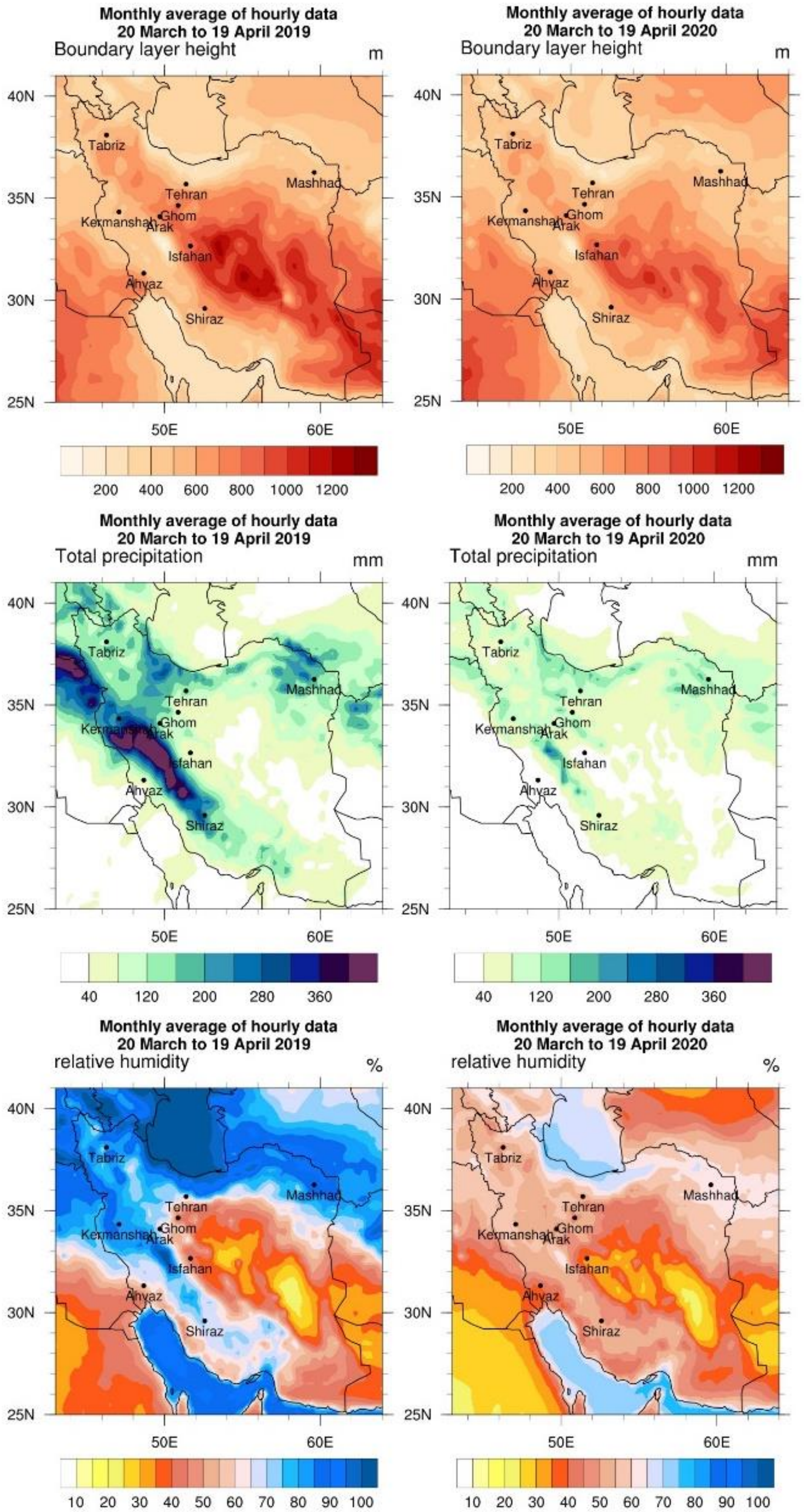

Fig. 5. The monthly averaged value of Planetary Boundary Layer Height (m), precipitation (mm), and Relative Humidity (%) in Iran for the period of 21st March to 21st April in 2019 and 2020.

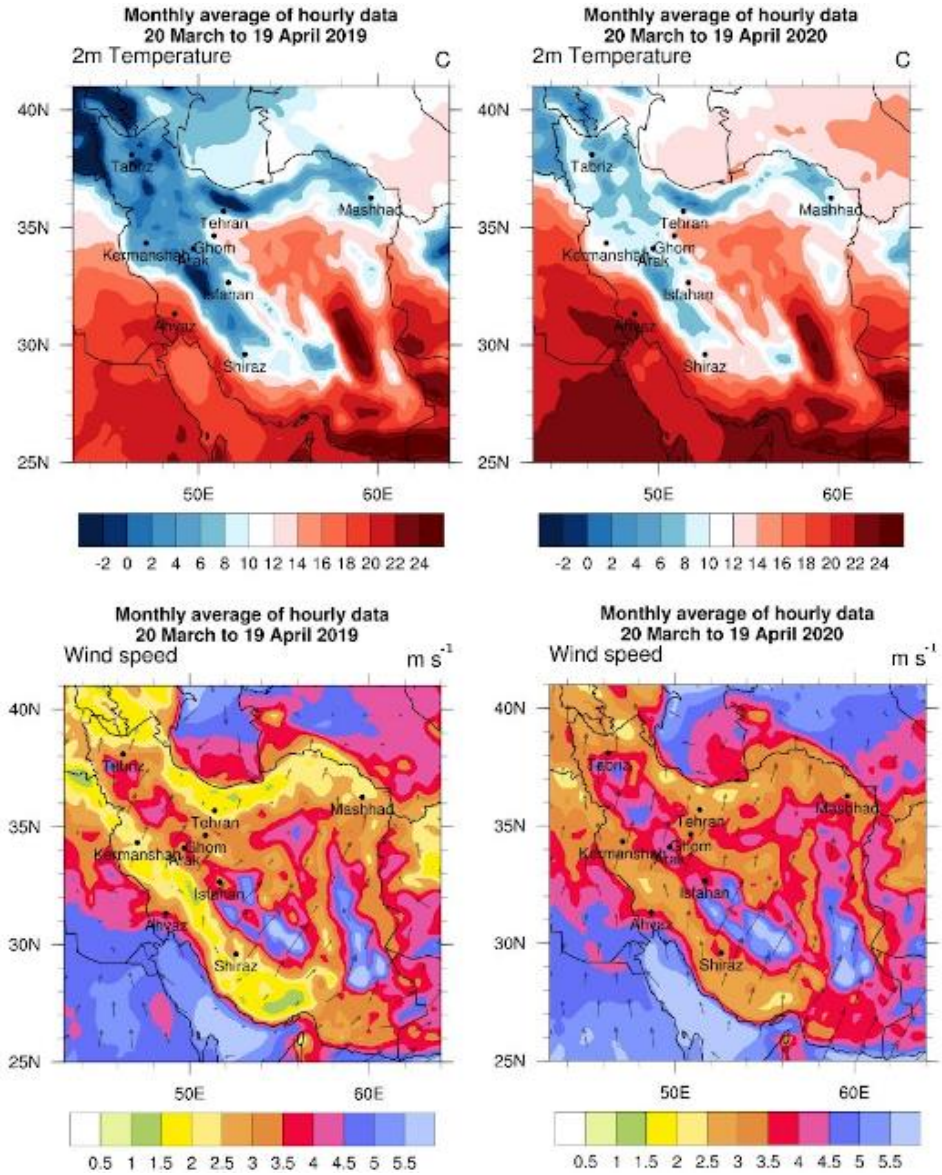

Fig. 6. The monthly averaged value of Temperature (°C), Wind Speed (m s^{-1}), and Wind Direction (°) in Iran for the period of 21st March to 21st April in 2019 and 2020.

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Mahsa Tamjidi: Data preparation.
Jong Ryeol Kim: Supervision and Project administration.

CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

ACKNOWLEDGEMENT

This project has received funding from the NU project (Nazarbayev Research Fund SOE2017004).

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Received for review, May 7, 2020
Revised, June 25, 2020
Accepted, June 27, 2020