Effect of restricted emissions during Covid-19 lockdown on air quality in Rabat – Morocco

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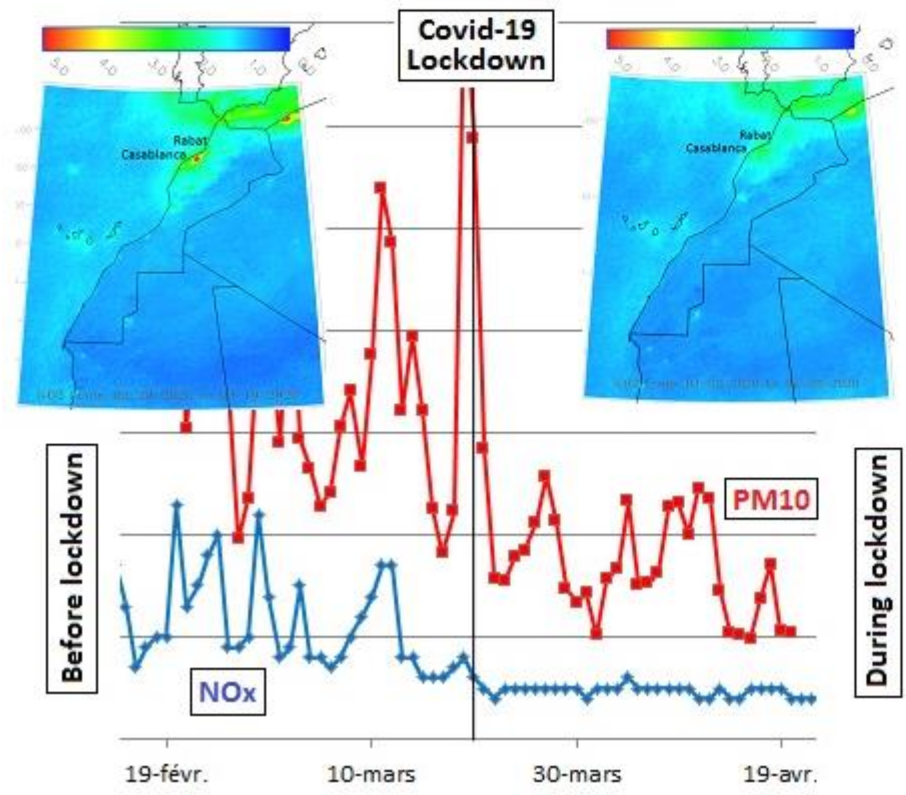
Graphical abstract



Abstract

The effect of restricted human activities due to the COVID-19 pandemic in Rabat city (Morocco) was studied, by analysing data of five criteria pollutants (NO, NO_2, $PM_{2.5}$, PM_{10}, and O_3) to highlight the effectiveness of restricted emissions on air quality. Overall, drastic reductions on NO (up to −94%), NO_2 (up to −51%), $PM_{2.5}$ (up to −45%), and PM_{10} (up to −53%) concentrations were observed during lockdown period compared to the first period (before lockdown). Spaceborne NO_2 column observations from TROPOMI on board Sentinel-5P, reveal unprecedented NO_2 decreases (up to −60%). By contrast, an increase of approximately 20% in ozone mean concentrations was observed, probably related to the reduction of nitrogen oxides and also of fine particles ($PM_{2.5}$) which leads to less scavenging of HO_2 and as a result greater O_3 production.

Keywords: Coronavirus, Lockdown, Anthropogenic emissions, Air quality, NOx, PM, O_3

1. Introduction

There is significant evidence that air pollution is associated with premature mortality (Lelieveld et al., 2015) and adverse health effects. According to the World Health Organization, 4.6 million individuals die annually from diseases and illnesses directly related to poor air quality (Cohen et al., 2017). Particulate matter with an aerodynamic diameter lower than 2.5 μm and 10 μm ($PM_{2.5}$ and PM_{10}), nitrogen oxides (NOx) and tropospheric ozone (O_3) are one of the greatest environmental problems of developed countries, indeed they are considered among the most threatening air pollutants, in urban environments, in terms of harmful effects on human health associated with respiratory and cardiovascular diseases and mortality (Pascal et al., 2013; Cohen et al., 2017).

In late December 2019, an unknown infectious disease, later named COVID-19, was identified in Wuhan, China (Na Zhu et al., 2020). The disease has rapidly spread from Wuhan to other areas and affected 196 countries worldwide by March 25, 2020, which raised intense attention internationally. To contain the escalation of the transmission of the virus, many countries have adopted dramatic measures to reduce human interaction, prohibiting private and public gatherings, restricting all forms of transportation (both within a city and across cities).

As a possible side effect of this unprecedented lockdown, human mobility and relevant production and consumption activities have since decreased significantly. Transport sector, industrial and manufacturing sector were heavily affected. But on the other hand, lockdown restrictions are expected to largely modify anthropogenic emissions of pollutants, both in terms of emitted mass and time variations (Menut et al., 2020). Several studies on the impact of lockdown measures on air quality have recently been published. Sicard et al. (2020) studied the effect of lockdown on air pollution in four Southern European cities (Nice, Rome, Valencia and Turin) and Wuhan (China). Compared to the same period in 2017–2019, strong reductions in NO_2 mean concentrations were observed in all European cities, ~53% at urban stations, comparable to Wuhan (57%), reductions in $PM_{2.5}$ and PM_{10} at urban stations were overall much smaller both in magnitude and relative change in Europe (~8%) than in Wuhan (~42%). By contrast, the daily O_3 mean concentrations increased at urban stations by 24% in Nice, 14% in Rome, 27% in Turin, 2.4% in Valencia and 36% in Wuhan during the lockdown in 2020. The same findings have been reported by Nakada et Urban (2020) in São Paulo (Brazil), Tobías et al. (2020) in Barcelona (Spain), Collivignarelli et al. (2020) in Milan (Italy), Sharma et al. (2020) in 22 cities covering different regions in India.

On the other hand, Bauwens et al. (2020); Tobías et al. (2020) have used spaceborne NO_2 column data from two high-resolution instruments, Tropospheric Monitoring Instrument (TROPOMI) on board Sentinel-5 Precursor and Ozone Monitoring Instrument (OMI) on Aura. Exceptional decreases in NO_2 columns were observed over widespread areas in China, Europe, Latin America, and the United Sates.

Morocco was confirmed as one of the countries affected by COVID-19, when the first case was confirmed in Casablanca on March 2, 2020. The government reacted decisively to the threat of the pandemic and declared a "health state of emergency" that went into effect on March 20 and included a nationwide lockdown. In this study, we carry out a rigorous investigation into this issue and estimate how lockdown affected air quality of Rabat (Capital city of Morocco), by studying the evolution of the nitrogen oxides (NO and NO_2), particulate matter ($PM_{2.5}$ and PM_{10}), and ozone (O_3) concentrations determined before lockdown (from February 20 to March 19) and during the lockdown (from March 20 to April 20).

2. Materials and methods

Rabat, capital city of Morocco, is located on the Atlantic coast, with an urban population of approximately 580,000 (2014) and a metropolitan population of over 1.2 million. Rabat is characterized by a Mediterranean climate with an annual mean air temperature of 15 °C (from 7 °C in January to 25 °C in August) and belongs to the sub-humid bioclimatic zone with an average annual precipitation of 560 mm.

During the studied period, the real-time monitoring data were provided by the automatic monitoring station of the Atmosphere Competence Center (PCMA) installed in the campus of the national higher school of mining of Rabat, using standard methods and equipment. Thermo scientific model

42i NO–NO_2–NOx analyzers, which are based on the most common used technique (chemiluminescence) for nitrogen oxides measurements. Ozone Analyzer O342e from ENVEA, using LED-based UV photometry technology, for O_3 measurements. Particulate matter ($PM_{2.5}$, PM_{10}) was determined with PALAS FIDAS® 200E continuous particle monitor , using an optical particulate monitoring spectrometer.

The concentrations of NO, NO_2, $PM_{2.5}$, PM_{10}, and O_3 were obtained at 15-minute intervals. Experimental data were initially analyzed to identify spurious data and values were organized in spread sheets as 1-hour means. Daily averages (24 h) have then calculated for the periods before (February 20th to March 19th) and during the lockdown (March 20th to April 20th), assessing the variation in the mean concentration (μg m^{-3}) between both periods, and their relative change (%).

In parallel, remote sensing NO_2 data, obtained by the Copernicus Sentinel-5 Precursor Tropospheric Monitoring Instrument (S5p/TROPOMI), has been used to assess tropospheric NO_2 background levels in a high resolution (3.5 × 7 km^2) continuous area (Ialongo et al., 2020).

In order to be able to interpret the evolution of pollutant concentrations before and during the confinement, meteorological parameters (temperature, relative humidity, and wind speed) were also determined. For this, the ERA5 data (http://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-single-levels?tab=form) were collected for the 2 studied periods. These meteorological data are reanalyses available at a spatial resolution of 0.25° and a temporal resolution of 1 hour.

3. Results and discussion

3.1. Meteorological data analysis for reference period selection

Meteorological data analysis is essential considering that weather phenomena have a massive influence on air quality. As shown in Table 1, average daily precipitation illustrates a similar situation between the lockdown and before lockdown periods, with low precipitation during the lockdown period. The recorded rainfall shows a total of about 2 mm d^{-1}. Furthermore, there were negligible variations in temperature with a variation of less than 1°C between periods. The average wind speeds over the periods are also very similar. Overall, it can be concluded that the conditions are similar for the two periods, thus preventing an overestimation of air quality.

Table 1. Averaged meteorological parameters observed in Rabat city before and during the lockdown.

	Temperature °C	**Wind speed** M s^{-1}	**Precipitation** mm d^{-1}
Mean BL	15,8	2,5	0,2
Mean DL	16,4	2,9	2,1
Difference	**0,6**	**0,4**	**1,9**

BL : Before Lockdown
DL : During Lockdown

3.2. Air quality monitoring

Experimental results were obtained from February 20 to April 20, 2020 at PCMA monitoring station. The obtained results are shown in table 2 and presented in Figs. 1-4, respectively, for nitrogen oxides (NO and NO_2), particulate matter ($PM_{2.5}$ and PM_{10}), and ozone (O_3). The amplitude of the concentration variation (ACV) was calculated to assess relative change (%) comparing the lockdown period to before lockdown, using the equation;

$$\mathrm{AVC} = \frac{\mathrm{y} - \mathrm{x}}{\mathrm{x}} \times 100\%$$

where x and y are the mass concentrations of a substance of interest before and during the control period for Covid-19, respectively.

3.2.1. Nitrogen oxides

From the obtained results, as shown in Fig. 1, exceptional decreases in nitrogen oxides levels were observed in the studied area. A decrease in the concentrations of NO (from 1.7 to 0.1 μg m^{-3}) and NO_2 (from 8.6 to 4.2 μg m^{-3}) was recorded, which corresponds to an AVC of −94% and −51%, respectively. This could be explained by the containment measures against the spread of the Covid-19, which caused sharp reductions in traffic and industrial activities. The magnitude of changes was similar to those recorded in European cities (~52%) and Wuhan in China (57%), where automobile exhausts are the major source of NOx (Sicard et al. 2020; Tobías et al., (2020).

Table 2. Mean concentrations of NO, NO_2, $PM_{2.5}$, PM_{10}, O_3, measured in Rabat city before and during the lockdown.

	NO $\mu g\ m^{-3}$	NO_2 $\mu g\ m^{-3}$	$PM_{2.5}$ $\mu g\ m^{-3}$	PM_{10} $\mu g\ m^{-3}$	O_3 $\mu g\ m^{-3}$
Mean BL	1,7	8,6	17,1	36,4	35,1
Mean DL	0,1	4,2	9,4	17,1	43,7
Variation in %	**−94**	**−51**	**−45**	**−53**	**+20**

BL : Before Lockdown

DL : During Lockdown

Nitrogen oxides ($NOx = NO_2 + NO$) are among the main drivers in air quality degradation in urban centers, due to their role as catalysts of tropospheric ozone formation, and as precursors of secondary inorganic aerosols, with consequences for climate and human health (Lelieveld et al., 2015). NOx emissions are mainly generated by combustion processes from anthropogenic pollution sources including transportation, energy production and other industrial activities (Wang et al., 2017; He et al., 2020a, 2020b).

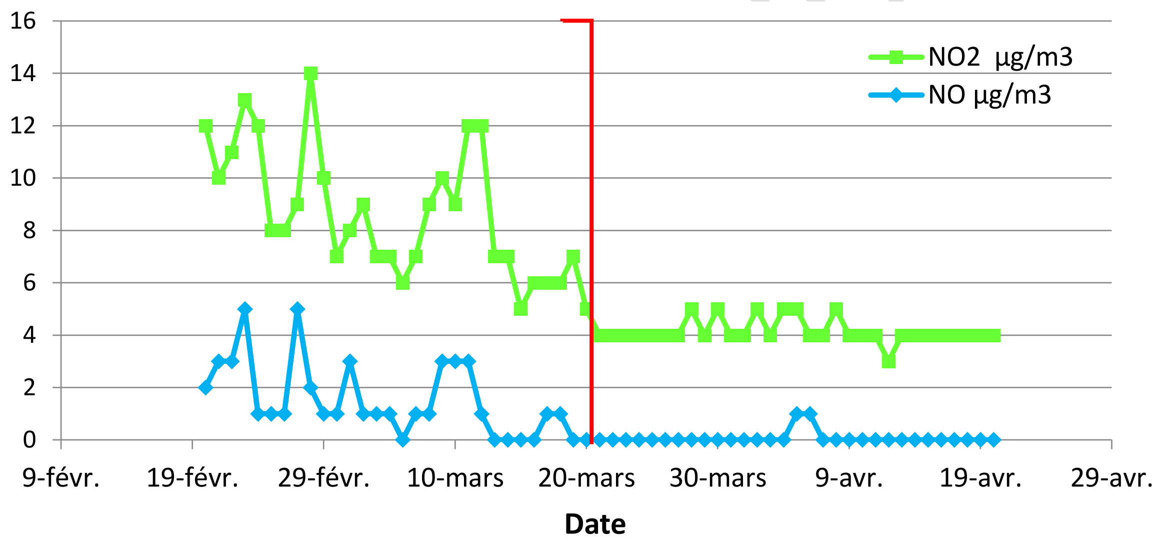


Figure 1. Daily NO and NO_2 mean concentrations ($\mu g\ m^{-3}$) determined at PCMA monitoring station from February 20, 2020 to April 20, 2020 in Rabat - Morocco

Daily NOx concentrations decrease is mainly attributed to the containment measures against the spread of the Covid-19, which caused sharp reductions in road traffic and fossil combustion. Recent researches have demonstrated that traffic emissions from heavy-duty diesel trucks are major sources of nitrogen oxides (Nakada et Urban, 2020; Wang et al., 2020) and is considered to be responsible for over half of NOx emissions and represents a higher proportion in urban areas.

On the other hand, NO_2 emissions were measured using TROPOMI instruments through Copernicus Sentinel-5P satellite. The satellite image (Fig. 2) provide comparison between the average of concentrations from 20 February to 19 March 2020 (panel a) and the average of concentrations from 20 March to 20 April 2020 (panel b). The NO_2 emissions reduced up to 60% due to lockdown, especially across the major cities such as Casablanca and Rabat, thus confirming the measures observed at PCMA monitoring station. Several studies have used satellite observations of NO_2 columns to assess the impact of covid-19 (Nakada et Urban 2020; Tobías et al. 2020; Zambrano-Monserrate et al., 2020).

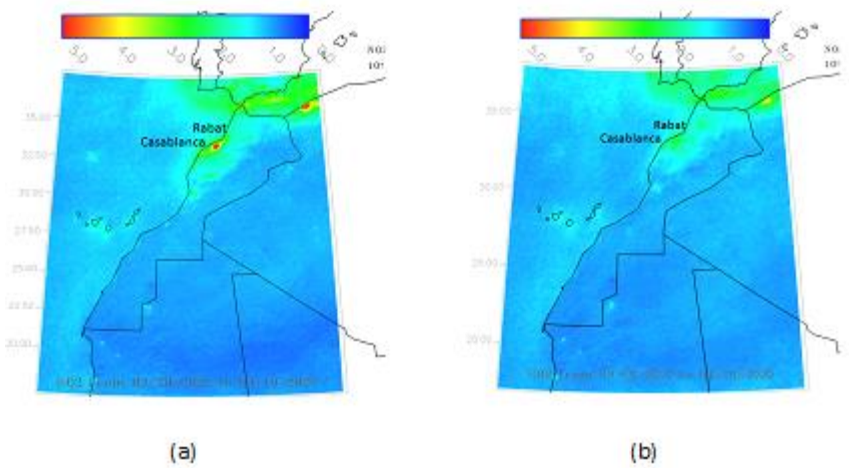


Figure 2. Average TROPOMI NO_2 tropospheric columns over Morocco (E15 molecules/cm^2), (a) before and (b) during the lockdown

3.2.2. Particulate matter

The particulate matter (PM) showed the same behavior (Fig. 3) as the nitrogen oxides during the Covid-19 control period compared with the reference period, in fact the mean concentrations decreased (from 17.1 to 9.4 µg m^{-3}) and from (36.4 to 17.1 µg m^{-3}), which corresponds to an AVC of −45% and −53%, respectively, for $PM_{2.5}$ and PM_{10}. The higher decrease in PM_{10} compared to $PM_{2.5}$ could be due to its greater contribution from anthropogenic sources (Klimont et al., 2017). The main source of PM_{10} in the urban background is road traffic, combustion of fuels, industrial sources, construction works, dust resuspension, Saharan dust episodes (Querol et al., 2009), and regional air mass transport which could have an influence on PM to the point of reducing the effects of local emission reduction. Aerosol particles $PM_{2.5}$ are also receiving worldwide attention, as they have a potential greater adverse effect on the health of human beings, especially on that part of the population living in urban areas influenced by high traffic density or industry (Dongarrà et al., 2010).

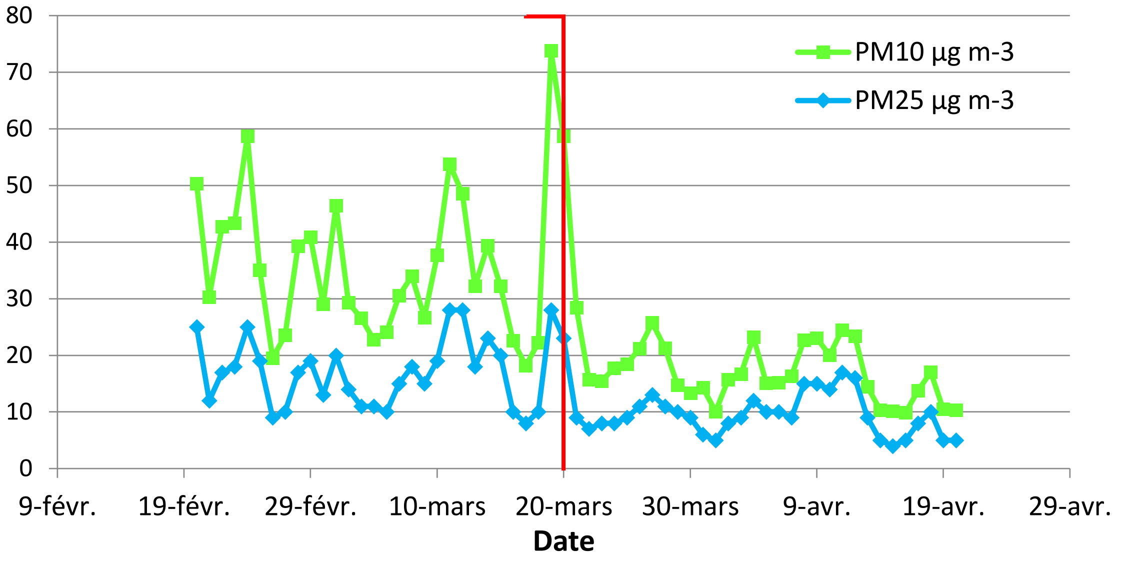


Figure 3. Daily $PM_{2.5}$ and PM_{10} mean concentrations (µg m^{-3}) determined at PCMA monitoring station from February 20, 2020 to April 20, 2020 in Rabat - Morocco

The reduction of PM_{10} (−53%) was likely attributable to the significant reduction in vehicular traffic given by the transfers restrictions imposed by the authorities considering that transports represent the main source of PM_{10} in Rabat. The effects of reducing local air pollution on PM_{10} concentrations might still be limited due to the contribution of long-range transported PM. Indeed, the back trajectory analysis portrayed that air quality in Rabat urban area is mainly affected by PM originating from the Mediterranean Basin (characterized by marine vessel emissions out of Western Europe and Northern Africa), local continental and from the near Atlantic Ocean (Othmani et al., 2020). The reduction of $PM_{2.5}$ of −45% can be attributed to the simultaneous reduction in the concentration of other pollutants such as NH_3, volatile organic compounds (e.g. benzene), and NOx which act as precursors to the formation of secondary $PM_{2.5}$ (Chen et al., 2017). Similar findings were reported by Nakada and Urban (2020) and Zambrano-Monserrate et al. (2020).

3.2.3. Ozone

By comparing mean concentrations before and during the lockdown, we observed that higher O_3 concentrations occurred during the lockdown. The daily O_3 mean concentrations increased considerably, from 35.1 to 43.7 µg m^{-3} which corresponds to an AVC of +20% (Fig. 4). This result is consistent with the recent literatures, for example, Sharma et al., (2020) reported an increase in O_3 in many cities covering different regions of India and Nakada et Urban (2020) observed an increase of approximately 30% in ozone concentrations in São Paulo.

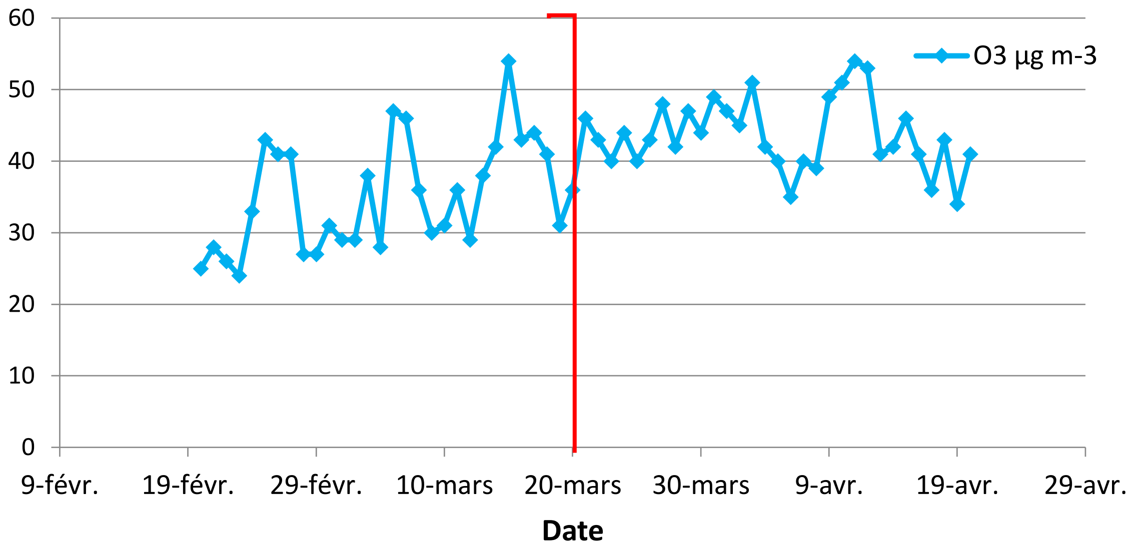


Figure 4. Daily O_3 mean concentrations (µg m^{-3}) determined at PCMA monitoring station from February 20, 2020 to April 20, 2020 in Rabat - Morocco

The photochemical processes related to tropospheric ozone formation have been extensively discussed in the literature. Ground-level O_3 is subject to in situ chemical reactions and physical processes and is directly affected by precursor emissions, temperature, solar radiation and other meteorological factors. A number of studies have examined the role of anthropogenic and meteorological factors in the formation of ozone and concluded that meteorological factors were not negligible, but anthropogenic factors were dominant (Yu et al., 2019). Li et al. (2019a, 2019b) found that the increasing trend cannot be simply explained by changes in anthropogenic precursor [NOx (where NOx = NO + NO_2) and volatile organic compound (VOC)] emissions, this is mainly due to aerosol chemistry rather than photolysis. In the troposphere, NOx reacts with volatile organic compounds (VOCs) to form O_3, and therefore, one would expect that O_3 would have decreased along with NOx during the control period for Covid19, however, this was not the case. In fact, the daily O_3 mean concentrations increased considerably (+20%). The increase in O_3 levels in the Rabat city can be explained by different possible combined causes. Firstly, the usual increase of insolation and temperatures (~3.7°C) from February to April leads to an increase in O_3. Secondly, the decrease of nitrogen oxide (−94%) reduces the O_3 consumption (titration, $NO + O_3 = NO_2 + O_2$), and causes an increase of O_3 concentrations. Thirdly, the decrease of NOx in a VOCs-limited environment might cause urban O_3 to increase, as opposed to the behavior at the rural-regional background, which is mainly NOx-limited (Monks et al., 2015). Silva et al. (2017), reported that at low VOC/NOx ratios, a typical situation of polluted urban centers, the system is VOC-controlled, and reducing NOx at constant VOCs leads to an increase of ozone concentrations. Finally, the observed increases in O_3 during the Covid-19 controls may be related to the observed decreases in fine particles. The decrease of $PM_{2.5}$ (−45%) promotes ozone formation due to the role of fine particles as scavenger of hydroperoxy radicals (HO_2) which would increase peroxy radical-mediated O_3 production (Li et al., (2019a, 2019b)). Liao and Seinfeld (2005) found that simulated surface layer O_3 concentrations can be reduced by 25-30% due to heterogeneous reactions on fine particulate matter using a coupled global chemistry-aerosol-climate model.

4. Conclusions

As it could be expected, significant air quality improvements were observed during the lockdown in the studied area, a strong decrease in the mean concentrations of specific air pollutants was recorded, NO (up to −94%), NO_2 (up to −51%), $PM_{2.5}$ (up to −45%), and PM_{10} (up to −53%). Overall, the significant declines in NOx and PM concentrations are mainly attributed to the containment measures against the spread of the Covid-19, which caused sharp reductions in traffic and industrial activities. However, the reduction in nitrogen oxides and particulate matter emissions did not fully eliminate air pollution, and O_3 actually increased (up to +20%). This result illustrates the importance of reactions that can occur between gaseous and particulate pollutants. Ozone increase can be explained by the lower titration of O_3 by NO due to the strong reduction in local

NOx emissions and by the drop in $PM_{2.5}$ which can lead to less trapping of hydroperoxy radicals (HO_2), which would increase peroxy radical-mediated O_3 production.

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