Atmospheric pollutants response to the emission reduction and meteorology during the COVID-19 lockdown in the north of Africa (Morocco)

Salah Eddine Sbai¹ • Farida Bentayeb¹ • Hao Yin²,³

Abstract
Climate and air quality change due to COVID-19 lockdown (LCD) are extremely concerned subjects of several research recently. The contribution of meteorological factors and emission reduction to air pollution change over the north of Morocco has been investigated in this study using the framework generalized additive models, that have been proved to be a robust technique for the environmental data sets, focusing on main atmospheric pollutants in the region including ozone (O₃), nitrogen dioxide (NO₂), sulfur dioxide (SO₂), particulate matter (PM₂.₅ and PM₁₀), secondary inorganic aerosols (SIA), non-methane volatile organic compounds and carbon monoxide (CO) from the regional air pollution dataset of the Copernicus Atmosphere Monitoring Service. Our results, indicate that secondary air pollutants (PM₂.₅, PM₁₀ and O₃) are more influenced by meteoro logical factors and the other air pollutants reported by this study (NO₂ and SO₂). We show a negative effect for PBHL, total precipitation and NW10M on PM (PM₂.₅ and PM₁₀), this meteorological parameters contribute to decrease in PM₂.₅ by 9, 2 and 9% respectively, before LCD and 8, 1 and 5% respectively during LCD. However, a positive marginal effect was found for SAT, Irradiance and RH that contribute to increase PM₂.₅ by 9, 12 and 18% respectively, before LCD and 17, 54 and 34% respectively during LCD. We found also that meteorological factors contribute to O₃, PM₂.₅, PM₁₀ and SIA average mass concentration by 22, 5, 3 and 34% respectively before LCD and by 28, 19, 5 and 42% during LCD respectively. The increase in meteorological factors marginal effect during LCD shows the contribution of photochemical oxidation to air pollution due to increase in atmospheric oxidant (O₃ and OH radical) during LCD, which can explain the response of PM to emission reduction. This study indicates that PM (PM₂.₅, PM₁₀) has more controlled by SO₂ due to the formation of sulfate particles especially under high oxidants level. The positive correlation between westward wind at 10 m (WW10M), Northward Wind at 10 m (NW10M) and PM indicates the implication of sea salt particles transported from Mediterranean Sea and Atlantic Ocean. The Ozone mass concentration shows a positive trend with Irradiance, Total and SAT during LCD; because temperature and irradiance enhance tropospheric ozone formation via photochemical reaction. This study shows the contribution of atmospheric oxidation capacity to air pollution change.

Keywords COVID-19 • Generalized additive models • Atmosphere • Pollution • Photochemical oxidation • Meteorological factors
1 Introduction

Aware of the state of degradation of its natural resources, Morocco has adopted an environmental policy based essentially on the concept of sustainable development. He intends to make environmental protection a factor in the country’s economic and social development. The national debate on regional planning and the organization in Morocco of the 22nd conference of the countries parties to the convention on climate change (COP 22) in 2016 show the effective commitment of Morocco, like several countries in development, to make the environment one of the components of sustainable development.

Morocco declared a state of health emergency and lockdown from Friday, March 20th in order to contain the spread of SARS-CoV-2 virus (Covid-19), while the country recorded its first positive case on March 2. The government very quickly decided on a series of measures, which were only put in place in European countries at stage 2 or 3 of the pandemic. COVID-19 was characterized as a pandemic on March 12th, 2020 and, as the number of cases increased, the government made very quickly a series of measures, which were only put in place in European countries at stage 2 or 3 of the pandemic. COVID-19 was characterized as a pandemic only put in place in European countries at stage 2 or 3 of the pandemic.

The COVID-19 pandemic has severely affected daily life, including the economic, social and health sectors. The restriction of human activities during the spread of COVID-19 had a major impact on air quality and climate change due to the decrease in the atmospheric pollutants levels like nitrogen dioxide, sulfur dioxide and carbon monoxide, etc. (Chelani. 2021 and 2022; Gautam 2020a and 2022; Berman and Ebisu 2020; Zambrano-Monserrat et al. 2020; Bao and Zhang 2020; Bassani et al. 2021). However, several studies have shown a sharp increase in ozone which could increase the atmospheric oxidative capacity (Sharma et al. 2020; Tobías et al. 2020; Gautam 2020b). In the atmosphere, ozone could transform into OH radicals in the presence of humidity, according to the two reactions $\text{O}_3 + \text{hv} \rightarrow \text{O}_2 + \text{O}(1\text{D})$ and $\text{O}(1\text{D}) + \text{H}_2 \rightarrow \text{O} + 2\text{OH}$ (Peng et al. 2015). Ozone could also be reacted with other pollutants that are not related to human activities like biogenic volatile organic compounds (BVOC) or volatile organic compounds (VOC) and sulfur dioxide (SO2), leading to the formation of secondary organic aerosols (SOA) or secondary inorganic aerosols (SIA) which represents a significant fraction of PM (Abis et al. 2021; Srivastava et al. 2018). This could explain the increase in PM or the small decrease found in comparison with other pollutants, according to results of several studies (Sbai et al. 2021b; Chauhan and Singh 2020; Dantas et al. 2020).

The metrological conditions can play a vital role during atmospheric oxidation, since the formation of oxidants (O3 and OH radical) is strongly controlled by meteorological parameters like humidity (Tillmann et al. 2010), UV radiation (Bais et al. 2018), temperature (Wu et al. 2011), and planetary boundary layer height (Su et al. 2018). COVID-19 LCD gives an important opportunity to study and analyze the transformation of many atmospheric pollutants and also the contribution of meteorological parameters in atmospheric pollution. Understanding the response of air pollution to emissions reduction due to COVID-19 LCD will provide important clues regarding health and emissions control and forecasting trends in air pollution.

Advances in the numerical methods recently of linear models enhanced the capability to understanding the atmospheric environmental processes (Ravindra et al. 2019). A mathematical basis for the assessment of atmospheric parameters, and providing comparative significance of different variables can be easily understood using statistical methods (Ravindra et al. 2016). Generalized additive models (GAM) is recently adopted as analytical methods in atmospheric environment by several researchers (Ravindra et al. 2019; Yin et al. 2021; Zhang et al. 2019a, b). GAMs model can be used to assess the consequence of air pollutants and climate change on human health, to evaluate the impact of metrological factors on atmospheric pollution level or primary and secondary air pollution relationship under different conditions. Furthermore, GAM model also was utilized to understand the driving forces of air pollution evolution and evaluate the efficiency of emission controls (Zhang et al. 2019a, b).

The change in air pollution level due to COVID19 LCD has been widely studied by several studies in Europe, Asia especially in China and India and also in South America such as US, Brazil, Mexico, and Argentina, etc. However, in Africa the study of climate change due to COVID19 LCD is very limited due to lack of data or access to dataset. In the Morocco atmospheric pollution data is not subject to distribution to the public. In addition, there are only 29 measuring stations distributed throughout the country do not provide sufficient temporal resolution of air quality, which requires the search for an optimal alternative source to carry out studies, based on high resolution data. PM10, PM2.5, NO2, SO2, NMVOC, SIA and O3 mass concentrations of Copernicus Atmosphere Monitoring Service Reanalysis (CAMSRA) data have been used. This study is the first in North Africa according to our knowledge which will focus on the global change in main atmospheric air pollution.

Atmospheric pollutants are greatly influenced by meteorological parameters, but secondary air pollutants are also influenced by other pollutants like primary air pollutants. We evaluate the individual effects of metrological factors...
(s meteos) on air pollutants formation and the individual effects of each pollutant (s pollutants) on the formation of the other air pollutants (secondary air pollutants) was investigated using GAM model. To this effect, the concentrations of main atmospheric pollutants in the region including ozone (O$_3$), nitrogen dioxide (NO$_2$), sulfur dioxide (SO$_2$), particulate matter (PM$_{2.5}$ and PM$_{10}$), secondary inorganic aerosols (SIA), non-methane volatile organic compounds (NMVOC) and carbon monoxide (CO) from the regional air pollution dataset of the Copernicus Atmosphere Monitoring Service (CAMS). This study provides useful insights into the contribution of photochemistry involving O$_3$ and OH oxidation as an alternative pathway to air pollution during emission reduction.

## 2 Study area

Located at the northwestern end of the African continent, Morocco has a privileged geostrategic position with a maritime frontage extending over approximately 3,500 km, opening onto the Mediterranean to the north, with a coast of approximately 500 km, and on the Atlantic Ocean to the West with a coastline of about 3000 km. The Mediterranean coast is rich in natural sites and landscapes with some points of high population density, in particular between Tangier and Casablanca. The Atlantic coast concentrates the largest agglomerations reaching the highest densities. It is served by a relatively dense road and communication network. It also has the largest hydrographic network since the largest rivers flow into the Atlantic Ocean. Morocco is bounded on the east by Algeria and on the south by Mauritania. The surface of Morocco reaches 710 850 km$^2$, of which a large part is covered with mountainous zones (figure S1).

The Moroccan climate is both Mediterranean and Atlantic, with a dry and wet season defined by a cold and wet season, the end of the hot period being marked by the October rains. The presence of the sea attenuates temperature variations, moderates the seasons and increases the humidity of the air (400 to 1000 mm of rainfall on the coast). In the interior, the climate varies according to the altitude. Summer wind blowing from the Sahara. In this season, the average temperatures are 22 ºC to 24 ºC. Winters are cold and rainy with frost and snow. The average temperature then changes from $-2$ ºC to 14 ºC and can drop to $-26$ ºC. In mountainous regions, precipitation is very high (more than 2,000 mm of precipitation in the Rif or even 1,800 mm in the Middle Atlas). Pre-Saharan and Saharan Morocco has a dry desert climate.

## 3 Methods

### 3.1 Atmospheric pollutants mass concentration data

The Copernicus Atmosphere Monitoring Service (CAMS) database produces daily air quality analyses and forecasts for the European and north Africa with higher horizontal resolution ($0.1^\circ \times 0.1^\circ$ (10 km x 10 km)) than is available from the global analyses and forecasts and horizontal coverage extends from 25.0° W to 45.0° E and 30.0°S to 70.0°N. The production is based on an ensemble of nine air quality forecasting systems across Europe. A median ensemble is calculated from individual outputs, since ensemble products yield on average performance than the individual model products. The spread between the nine models are used to estimate the forecast uncertainty. The data cover all study area were investigated, in terms of mass concentration of the different air pollutants before LCD (between 3rd and 28th February 2020) and During LCD (between 3rd and 28th April 2020). The daily average mass concentrations for main atmospheric pollutants including ozone (O$_3$), nitrogen dioxide (NO$_2$), sulfur dioxide (SO$_2$), particulate matter (PM$_{2.5}$ and PM$_{10}$), secondary inorganic aerosols (SIA) and non-methane volatile organic component (NMVOC) from the regional air pollution data of the Copernicus Atmosphere Monitoring Service CAMS (CAMS 2021).

### 3.2 Meteorological conditions data

The meteorological conditions significantly influence air pollutants formation and their evolution in atmosphere (Chen et al. 2020). Meteorological data used in this study including surface air temperature (SAT), relative humidity (RH), Eastward wind at 10 m (EW10M), Northward Wind at 10 m (NW10M), Total Precipitation (TP), Irradiance, Planetary Boundary Layer Height (PBLH) for the period extending from 3rd to 28th February (Before LCD) and 3rd to 28th April (during LCD) over north of Morocco, were downloaded from Giovanni earth data (Giovanni 2021).

### 3.3 Data analysis

All data were downloaded as NetCDF files from CAMS and Giovanni. Data visualization and preprocessing were performed by Panoply data viewer version 4.12.7.0. The ArcGis 10.8 was used for map representation using three-dimensional (3D) (latitude, longitude, and time) NetCDF file. For modelization, 3D data has been transformed into 2D and GAM model was conducted using the gam.
modeling function in the R package version 4.1.0 (open source statistical software and language) with the ‘mgcv’ library.

3.4 GAMs model

To assess the contribution of meteorological factors report above. We applied a statistical adjustment method based on the GAMs model. Moreover, the contribution of each pollutant to formation of others air pollutants was evaluated by GAM model. To explain the impact of individual factors on air pollutants, we used the effect of the smooth term $S(X_i)$ in GAM model, where $X_i$ is the individual factor and $S(X_i)$ represents the relative effect of meteorological factor on each pollutant mass concentration (Ravindra et al. 2019; Grüss et al. 2014; Yin et al. 2021; Zhang et al. 2019a, b). Generalized additive models (GAMs) are regression models where smoothing splines can be used instead of linear coefficients for covariates (Hastie and Tibshirani 1990). The additive model in the context of a concentration time series can be written in the form (Hastie and Tibshirani 1990):

$$\log(y_i) = \beta_0 + \sum_{j=1}^{n} s_j(x_{ij}) + \epsilon_i \tag{1}$$

where $y_i$ is the $i$th air pollution concentration, $\beta_0$ is the overall mean of the response, $s_j(x_{ij})$ is the smooth function of $i$th value of covariate $j$, $n$ is the total number of covariates, and $\epsilon_i$ is the $i$th residual with $\text{var}(\epsilon_i) = \sigma^2$, which is assumed to be normally distributed. Smooth functions are developed through an integration of model selection and automatic smoothing parameter selection using penalized regression splines, which while optimizing the fit, make an effort to minimize the number of dimensions in the model (Wood, 2006). The choice of the smoothing parameters is made through restricted maximum likelihood (REML) and confidence intervals are estimated using an unconditional Bayesian method (Wood 2006).

The GAMs model uses penalized smoothing splines to estimate the marginal effect of individual meteorological factors and pollutant concentrations on the air quality trends. Unlike previous studies based on the atmospheric chemistry model, this new statistical method based on long-term satellite observations provides an explicit solution to assess natural and anthropogenic impacts and estimate the role of emission control measures on air quality levels (Zhang et al. 2019a, b). The nonparametric shape of the model it is very flexible, allowing it to reveal the nonlinear effect of independent parameters. The smoothness of each function is controlled by the number of knots or effective number of degrees of freedom (Yin et al. 2021). Here, the smoothing parameters were estimated by restricted maximum likelihood (REML) (Wood 2004).

4 Results and discussion

To assess air pollution change during and before the LCD period, several studies have compared the pollutants level during the LCD period and the average of the pollutants level during the 3, 5 or 7 previous years to suppress meteorological conditions effect. CAMS dataset does not provide sufficient data for a few previous years and the pollution level changes from one year to another, for this reason we have compared the level of each pollutant for one month before LCD and one month during LCD, and we subtracted the meteorological effect using the GAM model.

4.1 Spatial patterns for main air pollutions ($O_3$, $NO_2$, $SO_2$, $PM_{2.5}$, and $PM_{10}$) before and during COVID-19 pandemic lockdown over north of Morocco

The south and east of Morocco are characterized by high-temperature levels which explain the high concentrations of ozone found in this area compared to the north and west.

![Fig. 1 Spatial patterns for $O_3$, $NO_2$ and $PM_{2.5}$ before and during COVID-19 pandemic lockdown over north of Morocco](image-url)
In addition, the car density in the south and east is lower than that of the north, which means that ozone titration by nitrogen oxide in the north is much more important than in the south-eastern. We also observed that O₃ mass concentration increased sharply during LCD over all the study area and does not exceed the OMS limit value 120ug/m³. The same results were found by several researches (Zhao et al. 2021), this behavior that can be due to the reduction of ozone titration by nitrogen monoxide (NO) carbon monoxide (CO) and sulfur dioxide (SO₂) during LCD period.

Figure 1b shows spatial distribution for NO₂ mass concentrations before and during LCD, we clearly observed that the highest concentrations of NO₂ are found in the north and the center (Casablanca, Rabat, and Marrakech), however we show that the level of NO₂ does not exceed limit value (40 µg/m³). During the LCD, NO₂ dropped dramatically in all the zone which is in agreement with all that is found by other studies in Europe (chauhan et al. 2021), Asia (Shen et al. 2021) or America (Cazorla et al. 2021), the decrease in NO₂ during LCD is due to the reduction in road traffic which represents the main source of NO₂. Moreover, we show also that the O₃ and NO₂ spatial distributions are inversely correlated which prove that the increase in O₃ during LCD is due to the reduction in its titration by NO₂.

The main sources of sulfur dioxide (SO₂) in Morocco are constituted by the burning of fossil fuels (e.g., oil and coal) and the smelting of mineral ores that contain sulfur. SO₂ is one of the important indicators of air pollutants that are strongly related to the combustion of coal, petroleum, and chemical fuel emissions. It is the major precursor of nucleation formation of new particles in the atmosphere; and when these processes occur in populated regions, they could increase the human exposure to ultrafine particles, the highest SO₂ mass concentrations are observed in the region of Casablanca, Rabat and tanguier, the major industrial cities in the country. Generally, the level of sulfur dioxide in the study area is very low (figure S2).

This Fig. 1c and Figure S2 show the spatial distribution of PM₂₅ (particulate matter with aerodynamic diameter less than 2.5um) and PM₁₀ (particulate matter with aerodynamic diameter less than 10um), we observe that PM₂₅ and PM₁₀ have similar distribution and PM₂₅ and PM₁₀ increase in the North and East of the study area during LCD. This finding can be explained by two arguments: the increase in the ozone level over the Mediterranean Sea and Atlantic Ocean in the north and northwest (Figure S3), promotes the formation of sea salt particles like iodine by O₃ oxidation or OH radical oxidation (Sbai and farida 2019b; Tham et al. 2021). In addition, sea salt particle can be transported by the north–south or west–east direction wind and contribute to increase in PM. Besides, the industrial activities especially phosphate production has not been completely suspended. Some study also indicate an increase in PM accumulation mode by 20%, this was explained by improvement of nucleation and growth process during the LCD period, due to the higher formation rate of 2 nm particles and the subsequent growth rate (Shen et al. 2021).

4.2 Daily variation for O₃, NO₂, CO, SO₂, PM₂₅, PM₁₀ and SIA before and during COVID-19 pandemic lockdown in the Casablanca

Figure 3 shows daily variation for O₃, NO₂, CO, SO₂, PM₂₅, PM₁₀ and SIA before and during of COVID-19 pandemic LCD in the Casablanca industrial capital of Morocco. Daily variation of ozone mass concentration during and before LCD display the same trends, O₃ slowly increases after the sun rises from the morning at 8:00 a.m. and reaches its maximum at 1:00p.m. at noon, afterward it remains stable at 120ug/m³ during the LCD (Fig. 2a), this behavior can be explained by the reduction in gases titrating (nitrogen monoxide and carbon monoxide) after 10:00a.m (Fig. 2b, c). In addition, the increase in temperature and solar radiation during the day promotes the production of ozone. The highest concentrations of NO₂ and CO were found during the morning between 8:00 and 10:00 (Fig. 2b, 2c), during the peak road traffic period that represents their main source, NO₂ before and during LCD have same trends indicating no change in the emission source. Daily variation of PM₂₅, PM₁₀ and SIA indicate no special change during the morning or in the middle of the day their concentrations remain stable throughout the day except a slight increase for PM₂₅ similar diurnal variations in PM₁₀ and PM₂₅ concentrations were found.

4.3 Marginal effect of individual meteorological variables s(meteos) on PM₂₅ and PM₁₀ mass concentration

Figure 3 and figure S4 show marginal effect of individual meteorological variables s(meteos) on PM₂₅ and PM₁₀ mass concentration. A negative effect for PBHL, total precipitation and NW10M on PM (PM₂₅ and PM₁₀), this meteorological parameters contribute to decrease in PM₂₅ by 9, 2 and 9% respectively, before LCD and 8, 1 and 5% respectively during LCD (Table 1). However, a positive marginal effect was found for SAT, Irradiance and RH that contribute to increase PM₂₅ by 9, 12 and 18% respectively, before LCD and 17, 54 and 34% respectively during LCD. In addition, Wu et al. 2019 was study meteorological effect on PM₂₅ using GAM model and show a positive correlation between RH and PM₂₅. The relationship between (SAT & Irradiance) and (PM) exhibits the role of
photochemistry in the formation of PM especially during emission reduction, this result can be due to the rise in temperature that can leads to increase in precursor gases emission like VOC and BVOC and oxidants (O$_3$ and OH radical) that can promotes the formation of PM by secondary pathway (Friedman et al. 2016; Sbai et al. 2021a). Negative value of NW10M represents SW10M and shows inverse correlation with PM. However, the NW10M display positive effect, this can be explained by the transport of sea salt particles from ocean in the north. In addition, several studies have reported that sea salts particles especially iodine particle contribute to PM$_{2.5}$ (Shi et al. 2021). West Wind at 10 m (WW10M) the negative values of EW10M, show a positive effect which indicate the contribution of sea salt particles transported from the Mediterranean Sea. However, EW10M (positive values) its effect remains almost null which shows that there is no contribution of the dust mineral particles from Sahara.

Planetary boundary layer height (PBLH) is an important parameter in the dilution of near-surface pollutants and vertical mixing. However, the relationship between PBLH and surface pollutants, especially (PM$_{2.5}$ and PM$_{10}$) concentration is not yet well understood (Su et al. 2018). We show a negative effect for PBHL on PM mass concentration, because their emission or secondary formation mainly occurs at the surface. A recent study reported a negative correlations PBHL and PM for most cases, and their relationship depends on location, meteorological conditions, and season (Su et al. 2018). Also, an independent PBLH–PM relationship is observed over the clean area, whereas negative correlations are found over the polluted areas. Relatively strong dependence are observed when the PBLH is low and PM level is high (Su et al. 2018). The absorbing aerosol has a potential factor influencing the PBLH–PM relationships, much higher absorbing aerosol loading is reported to have strong interaction with the PBLH via a positive correlation (Ding et al. 2016; Dong et al. 2017).

The positive correlation between PM mass concentrations and the RH due to the heterogeneous reactions and the formation of SOA via photochemical reaction that can enhanced under high RH level, because reaction of water molecule with O(1D) oxygen atoms is the main pathway for OH radicals formation (Wang et al. 2016; Q. Zhang et al. 2019a, b; Sbai and Farida 2019a, b). Thereby, causing an increase in PM mass concentration. Several studies have observed that PM increase with RH and this was partially explained by the aqueous-phase reactions, gas-particle partitioning and water uptake (Jia and Xu 2014; Qu et al. 2015).
4.4 Marginal effect of individual pollutants (O₃, NO₂, SO₂, NMVOCs) mass concentration on PM (PM₁₀ and PM₂.₅) level

PM₂.₅ and PM₁₀ display same response to individual pollutants marginal effect, PM and O₃ show a negative correlation during LCD that growth with O₃ level. O₃ contributes to a slight decrease (6%) in PM₂.₅ (Fig. 4). High ozone level promote fragmentation reactions that can generates species with high volatility and low molecular weight that does not effectively condense to form particles and consequently PM mass decrease, this can also be explained by the positive correlation found before LCD period when the atmosphere is loaded with precursor gases that can be oxidized by ozone and formed secondary aerosols. Some researchers reported that PM and O₃ show a nonlinear relationship since O₃ increases with PM at low to moderate and declines at higher PM (Buysses et al. 2019). The PM gas precursors emissions especially VOCs and SO₂ has been reduced due to the suspension of industrial activities and the increase of oxidants (O₃ and OH) during LCD can contribute to heterogeneous reactions at the particle surface which lead to decline PM mass (Ding 2003). That could explain the negative correlation between ozone and PM. Besides, sulfur dioxide has a positive correlation with PM and contributes significantly to PM mass concentration by 29 and 22% during LCD and by 44 and 41% before LCD for PM₂.₅ and PM₁₀ respectively (Table1). Evidently, the high contribution before LCD due to high SO₂ level, this finding is most likely due to the formation of sulfate particles from SO₂ oxidation, which contributes to the increase in the mass of PM. Jiang et al. show that the sulfate is the dominant component in PM in the atmosphere of Guangzhou in china (Jiang et al. 2019). Wu et al. was study SO₂ effect on PM using GAM model and shows a positive correlation between SO₂ and PM₂.₅ (Wu et al. 2017).

Fig. 3 Marginal effect of individual meteorological variables including: Humidity (RH), Surface air temperature (SAT), wind direction including Eastward wind at 10 m (EW10M) Northward Wind at 10 m (NW10M), Total Precipitation (TP), Irradiance, Planetary Boundary Layer Height (PBLH) on PM₂.₅ mass concentration. Shaded bands represents the point wise 95% confidence interval. The estimated degrees of freedoms (EDFs), which show the linear or nonlinear degree of fitting, corresponding to the individual terms are noted in each figure. An EDFs of 1 indicates a linear effect.
### Table 1 Summary of marginal effect of individual meteorological variables (meteos) and individual pollutants (pollutants)

| Pollutants | Average Mass Concentration $\mu g/m^3$ | S(meteos)% | S(pollutants)% |
|------------|----------------------------------------|-------------|----------------|
|            |                                        | S(RH) | S(IRRadiance) | S(TP) | S(PBHL) | S(T) | S(NW10M) | S(EW10M) | S(PM2.5) | S(PM10) | S(SO2) | S(NO2) | S(NMVOC) |
| **During Covid19 lockdown** | | | | | | | | | | | | | |
| O$_3$      | 102.1                                  | 20   | 10            | 0     | 10      | 50   | 5         | 5         | 10       | 10      | 49     | 12     | 19     |
| PM$_{2.5}$ | 13.0                                   | 34   | 12            | 17    | 8       | 17   | 4         | 8         | 6        | 50      | 29     | 12     | 3      |
| PM$_{10}$  | 21.1                                   | 5    | 27            | 7     | 4       | 18   | 17        | 22        | 7        | 54      | 22     | 13     | 4      |
| SO$_2$     | 4.1                                    | 24   | 36            | 1     | 6       | 30   | 0         | 3         | 48       | 16      | 16     | 4      | 16     |
| NO$_2$     | 3.8                                    | 11   | 11            | 10    | 23      | 11   | 0.0       | 34        | 27       | 8       | 8      | 38     | 19     |
| SIA        | 4.6                                    | 20   | 0.0           | 10    | 0       | 30   | 0.0       | 0.0       | 20       | 0       | 0      | 33     | 20     | 27     |
| **Before Covid19 lockdown** | | | | | | | | | | | | | |
| O$_3$      | 76.2                                   | 17   | 35            | 13    | 9       | 17   | 0         | 9         | 25       | 38      | 15     | 13     | 10     |
| PM$_{2.5}$ | 8.1                                    | 18   | 54            | 2     | 9       | 9    | 9         | 0         | 9        | 31      | 44     | 9      | 7      |
| PM$_{10}$  | 12.7                                   | 29   | 43            | 7     | 10      | 12   | 0         | 0         | 7        | 41      | 41     | 10     | 7      |
| SO$_2$     | 9.8                                    | 24   | 61            | 1     | 6       | 6    | 1         | 1         | 30       | 5       | 0      | –      | 45     | 20     |
| NO$_2$     | 9.4                                    | 21   | 48            | 1     | 7       | 17   | 0         | 6         | 26       | 0       | 0      | 43     | –      | 32     |
| SIA        | 4.9                                    | 25   | 51            | 1     | 6       | 13   | 0         | 4         | 20       | 0       | 0      | 30     | 20     | 27     |
During LCD the emission of anthropogenic VOC was reduced due to restriction of industrial activities. However, the BVOC emission enhanced with temperature. In addition, the formation of fine particles by oxidation of BVOC like isoprene and α-pinene decreased with increase in NO₂ levels due to the formation of high volatility products (Ng et al. 2007), which explains the reversal NO₂ dependence of PM during LCD (Fig. 4). On the other hand, the positive NO₂-PM correlation obtained before LCD is explained by the presence of anthropogenic VOCs which can be oxidized by ozone, nitrate radical (NO₃) or OH radicals and produces secondary organic aerosols (SOA) which represent a large fraction of PM (Mancilla et al. 2015; Waring and Wells 2015). The negative correlation of the NO₂-PM during LCD versus positive correlation before LCD could be the result of a number of factors: under high-NO₂ levels (before LCD), RO₂ reacts predominantly with nitrogen monoxide, while under low-NO₂ levels (during LCD) peroxy radicals react mainly with HO₂. The higher PM formation under high NO₂ conditions due to alkoxy radicals (RO) formation that isomerizes rather than fragments (Baldwin et al. 1977). The isomerization leads to the formation of large hydroxy-carbonyls (CHO₂), multifunctional products with low volatility that can be condensed in the particle phase and consequently contribute to increasing PM mass concentration. Furthermore, the isomerization depends on the size of RO radicals (Atkinson et al. 2006). Moreover, higher PM level observed under high-NO₂ conditions due to non-volatile organic nitrate formation (Ng et al. 2007). Also, we observed a positive trend between NMVOC and PM, especially at a mass concentration (> 7 μg/m³) and contributes to a slight increase in PM. The NMVOC can be considered as precursor gases their oxidation by ozone or OH radical leads to the formation of low volatility species which can condense and form particles, however their effect remains very moderate due to their low concentration in the region.

4.5 Marginal effect of individual meteorological variables (meteos) on O₃ mass concentration

The Ozone mass concentration shows convincing tendency of increase with RH, PBLH, Irradiance, Total precipitation, and SAT (Fig. 5). Temperature and Irradiance enhance photochemical ozone formation during the LCD period and caused an increase in O₃ by 50 and 10% respectively compared to other meteorological parameters (Table 1). Higher levels of solar irradiation could promote the rise of O₃ at the surface because intense solar radiation can lead to the enhancement of photochemical reactions producing ozone (Jasaitis et al. 2016). In addition, the increase in temperature enhance VOC and BVOC emission that can lead to O₃ formation (Bai 2021). Ozone mass concentrations in the upper boundary layer are higher than in the lower boundary layer (He et al. 2021), higher boundary layer (PBHL) is conducive to the transport of ozone from the upper layer, which can explain the positive correlation obtained for PBLH greater than 1000 m that caused an increase to O₃. Humidity contributes to increase ozone by 20% at RH (< 60%) during LCD. However, we show a negative correlation between RH and O₃ at RH (> 60%) because high RH contribute to the destruction of ozone by a catalytic reaction cycle resulting in enhanced ozone
destruction causes the formation of hydroxyl (OH) and hydroperoxy (HO₂) radicals. Moreover, NW10M and EW10M seem to have relatively little effect on the O₃ level. EW10M contribute to a low decrease in O₃ because high ozone levels are found in the west over sea, SW10M has a negative effect that decrease with reduction in wind speed (Fig. 5). Ma et al. used GAM to evaluate the complex nonlinear relationships between O₃ concentration and the meteorological factors driving O₃ mass concentration from 2013 to 2017 in Lanzhou in Western China and show that air temperature was the main factor for O₃ concentration, which is in perfect agreement with our study (Ma et al. 2020).

4.6 Marginal effect of individual pollutants (PM₁₀, PM₂.₅, NO₂, SO₂, NMVOC) mass concentration on ozone level

Figure 6 shows a negative correlation between ozone and PM (PM₂.₅ and PM₁₀) contributing to drop in ozone by about 10% during LCD and 38% respectively before LCD (Table 1). This can be explained by the photochemical aging of particles via ozone and OH radical oxidation, leading to changes in the chemical and physical properties of particles (Kang et al. 2018). Some studies discovered that SOA formed by O₃ and OH oxidation of VOCs absorb UV irradiation at atmospherically wavelengths (Romanosky et al. 2016), leading to rich photochemistry within the particles (aging) such as direct photodissociation of carbonyl (Mang et al. 2008) and peroxide (Epstein et al. 2013). Photochemical reaction into the oxidized particle contributes to their aging these reactions lead to a loss in the mass of the particles (Walser et al. 2007). We show also a negative marginal effect of SO₂ on ozone which amplifies with the increase of SO₂ mass concentration and causing a decrease in O₃ by 49% during LCD and 15% before LCD (Fig. 6), this behavior can be due to heterogeneous oxidation of SO₂ by O₃ and sulfate particle formation.

The NOₓ has a dual impact on ozone concentration, since that can contribute to the production and depletion of ozone, during LCD period nitrogen oxide (NO₂ and NO) mass concentration decrease and consequently ozone depletion via NO reaction, which can explain the positive correlation between ozone and NO₂ during LCD period.

![Fig. 5 Similar to Fig. 3 but for ozone](image_url)
that contributed to increase $O_3$ by 12%. Before LCD we find a negative effect of NO$_2$ because under high NOx level $O_3$ depletion via NO reaction more important than $O_3$ production via NO$_2$ reaction because the rate constant of NO reaction with ozone is almost 1000 times higher than that of NO$_2$ reaction with ozone, that can explain the negative correlation before LCD. In our previous study we have shown that ozone depletion has decreased by 50% during LCD (Sbai et al. 2021b).

Non-methane volatile organic compounds (NMVOCs) were widely emitted from a variety of sources, including the transportation sector, solvent use, industry and biomass burning (Li et al. 2017). The NMVOCs are important ozone gas precursors and affect strongly the tropospheric ozone chemistry and play key roles in $O_3$ formation (Li et al. 2019), which is in perfect agreement with the positive correlation obtained in this study (Fig. 6). Previous studies revealed that ethylene, toluene, xylene and propylene are estimated to be the key NMVOC precursors in ozone formation (Li et al. 2017).

### 4.7 Marginal effect of individual meteorological variables s(meteos) on primary air pollutants (SO$_2$ and NO$_2$) mass concentration

Figure S6 and S7 represent the effect of individual meteorological variables s(meteos) on primary air pollutants (SO$_2$ and NO$_2$) mass concentration. We show a negative dependence of NO$_2$ to RH, total precipitation and irradiance, causing a decrease in NO$_2$ by 11, 9 and 11% respectively during LCD and 21, 1 and 48% respectively before LCD (Table 1). The high level of water vapor in the atmosphere promotes NO$_2$ conversion to nitric acid (HNO$_3$) and SO$_2$ to sulfuric acid (H$_2$SO$_4$), which explains the negative effect of RH. Furthermore, high humidity and irradiation enhanced OH radical formation by the photolysis of ozone in the presence of water vapor, consequently OH radical react with SO$_2$ and form sulfur trioxide (SO$_3$) that can associated with water molecule to produce H$_2$SO$_4$. The negative marginal effect of PBHL indicates that NO$_2$ and SO$_2$ are mainly controlled by primary emission from the surface. The SAT shows a positive correlation with both NO$_2$ and SO$_2$ and we have observed the same trend before the end during LKD. Some studies found that temperatures above 40 $^\circ$C contributed to the increase of NO$_2$ by 120%, this finding is explained by the influence of temperature on evaporative emission rates or the association between meteorological parameters essential to NO$_2$ and surface temperatures (Pearce et al. 2011). Previous studies report also a positive relationship between (NO$_2$ and SO$_2$) and temperature during heat waves (Theoharatos et al. 2010) and non-heat wave periods using GAMs models (Pearce et al. 2011). We have observed a linear positive effect of WW10M on SO$_2$ however SW10M display a small effect; this can be explained by the location of industrials sites in North and West. EW10M has a positive effect on NO$_2$ level but SW10M displays a negative effect, both decreases with wind speed because in north and east car density is high and contributed to high NO$_2$ level production in this area.
4.8 Marginal effect of individual meteorological variables s(meteos) vs marginal effect of individual pollutants s(pollutants)

Figure 7 shows the marginal effect of the pollutants s(pollutants) and the meteorological factors s(meteos). The s(meteos) and s(pollutants) values indicate that the secondary pollutants (PM$_{2.5}$, PM$_{10}$ and O$_3$) are more influenced by the other pollutants and the meteorological parameters reported by this study in comparison to NO$_2$ and SO$_2$. The s(meteos) and s(pollutants) contribute to O$_3$ average mass concentration by 28.6 g/m$^3$ and 71.4ug/m$^3$ during LCD and by 9.1 $\mu$g/m$^3$ and 67.1 $\mu$g/m$^3$ before LCD respectively. While s(meteos) contributes to PM$_{2.5}$ and PM$_{10}$ by 1.5 $\mu$g/m$^3$, 0.6 $\mu$g/m$^3$ before LCD and 0.7 $\mu$g/m$^3$ and 0.6 $\mu$g/m$^3$ respectively during LCD. Moreover, s(pollutants) contributes to PM$_{2.5}$ and PM$_{10}$ by 6.6 $\mu$g/m$^3$ and 12.1 $\mu$g/m$^3$ before LCD and by 12.3 $\mu$g/m$^3$ and 20.4 $\mu$g/m$^3$ during LCD respectively (Fig. 8). This finding shows that meteorological factors could not explain the increase in PM and ozone during LCD, so that the main reasons for this increase were photochemical phenomena involving O$_3$ and OH radical oxidation and chemical process effects. That show also that atmospheric potential oxidation is enhanced during LCD due to rise in ozone and some radicals like OH and HO$_2$ that can be produced from O$_3$ photochemistry. In addition, we show that s(meteos) increase during LCD for all pollutants due to decline in some pollutants concentration. The difference between PM$_{2.5}$ and PM$_{10}$ dependence due to influence of sulfate and nitrate particles that have a size distribution > 2.5 $\mu$m (Zhuang 1999). For SO$_2$ and NO$_2$ are controlled rather by primary emissions that can explained their slight dependence. Ozone and SIA were not influenced in the same way as other secondary pollutants (PM$_{2.5}$ and PM$_{10}$) by metrological factors s(meteos) and other pollutants s(pollutants) because they depend on other atmospheric pollutants that are not reported by this study such as VOC, BVOC, and ammonia.

5 Conclusion

In order to assess the air quality status of Morocco during the (COVID-19) LCD, we have studied the change in air pollution due to COVID-19 LCD over the north of Morocco. During COVID-19 LCD emission of primary air pollution declined due to restriction of human activities which gave us an opportunity to assess the atmospheric oxidation capacity and its contribution to air pollution. The spatial distribution of O$_3$ shows high concentrations in the south and east of Morocco. However, the highest concentrations of NO$_2$ are found in the north and the center (Casablanca, Rabat, and Marrakech). The PM$_{2.5}$ and PM$_{10}$ display similar distribution, high levels found in the North and East of the study area during LCD. We observed the increase in secondary pollutants (PM$_{10}$, PM$_{2.5}$, SIA and O$_3$) despite the emissions reduction contrary to several studies, greatly developed our curiosity to discover the factors driving this trend. We have adopted GAM model as an analysis method to evaluate the contribution of
meteorological parameters s(meteos) as well as the contribution of each pollutant s(pollutants) to atmospheric pollution. The results show a positive effect for s(meteos) on Ozone, PM (PM$_{10}$, PM$_{2.5}$) and SIA. This finding can be explained by enhancement in photochemical reaction involving O$_3$/OH oxidation of VOC, BVOC and SO$_2$ leading to SOA and SIA particles formation, rise in s(meteos) effect on PM and SIA under high oxidants level (during LCD) can confirm this conclusion. We show also a strong increase in O$_3$ and PM over Mediterranean Sea (west) and Atlantic Ocean (north) during LCD, which can be due to sea salt oxidation that enhanced under high level in atmospheric oxidants (O$_3$ and OH radical). Moreover, sea salt particles transported by the wind towards the urban environment and contribute to PM increase over Morocco; this hypothesis can be supported by the positive correlation between (WW10M, NW10M) and PM. This study shows that LCD can not be sufficient sometimes to improve air quality, for this reason another policy measure must be adopted.

**Authors contributions** SES: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Writing-original draft, Visualization. FB supervision. HY Software and Validation.

**Funding** Not applicable.

**Declarations**

**Conflict of interests** The authors declare no competing interests.

**Ethics approval** This article does not contain any studies with human participants or animals performed by any of the authors.

**Consent to participate** Not applicable.

**Consent for publication** Not applicable.

**Data availability** Data are available by contacting the corresponding author, the data for the pollutant concentration is Available at Copernicus Atmosphere Monitoring Service European air quality forecasts website: https://ads.atmosphere.copernicus.eu/cdsapp#!/ search and metrological data can be found at Giovanni earth website: https://giovanni.gsfc.nasa.gov/giovanni/.

**Supplementary Information**

The online version contains supplementary material available at https://doi.org/10.1007/s00477-022-02224-z.

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