The Multi-Time Scale Changes in Air Pollutant Concentrations and Its Mechanism before and during the COVID-19 Periods: A Case Study from Guiyang, Guizhou Province

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Abstract: The lockdown during the coronavirus disease 2019 (COVID-19) pandemic provides a scarce opportunity to assess the efficiency of air pollution mitigation. Herein, the monitoring data of air pollutants were thoroughly analyzed together with meteorological parameters to explore the impact of human activity on the multi-time scale changes of air pollutant concentrations in Guiyang city, located in Southwest China. The results show that the COVID-19 lockdown had different effects on the criteria air pollutants, i.e., PM$_{2.5}$ (diameter $\leq 2.5$ µm), PM$_{10}$ (diameter $\leq 10$ µm), sulfur dioxide (SO$_2$), nitrogen dioxide (NO$_2$), carbon monoxide (CO), and ozone (O$_3$) concentrations. The lockdown caused a significant drop in NO$_2$ concentration. During the first-level lockdown period, the NO$_2$ concentration declined sharply by 8.41 µg m$^{-3}$ (45.68%). The decrease in NO concentration caused the "titration effect" to weaken, leading to a sharp increase in O$_3$ concentration. Although human activities resumed partially and the "titration effect" enhanced certainly during the second-level lockdown period, the meteorological conditions became more conducive to the formation of O$_3$ by photochemical reactions. Atmosphere oxidation was enhanced to promote the generation of secondary aerosols through gas–particle transitions, thus compensating for the reduced primary emission of PM$_{2.5}$. The implication of this study is that the appropriate air pollution control policies must be initiated to suppress the secondary generation of both PM$_{2.5}$ and O$_3$.

Keywords: coronavirus disease 2019 (COVID-19); lockdown; atmospheric pollutants; meteorological conditions; secondary aerosol formation; Guiyang

1. Introduction

The coronavirus disease 2019 (COVID-19) pandemic has caused unprecedented socioeconomic impact around the world [1]. In order to curb the viral transmission among humans, the State Council of China issued the National Emergency Plan for Public Emergencies, which set out the strictest lockdown measures and almost completely stagnated economic activities related to transportation and movement [2]. The lockdown measures included the partial or total closure of international borders, schools, and non-essential businesses, in addition to the restriction on non-essential movement of citizens [3]. Wuhan, the capital city of Hubei Province, announced the closure on 23 January 2020. Subsequently, other major Chinese cities/counties also followed suit. Localities determined the level of early warning according to the severity of harm, urgency, and developmental degree that may be caused by COVID-19, inclusive of four levels, which are level I (particularly serious), level II (serious), level III (more serious), and level IV (general) [4]. COVID-19 lockdown caused a reduction in the levels of human activities, which is essentially similar to the temporary emission control imposed on pollution sources during major conferences or sporting events. The difference is that COVID-19 lockdown had a wider impact and lasted longer [5]. Anthropogenic activities and the emissions from their pollution sources were
substantially reduced during the lockdown period, thus creating a rare “natural laboratory” to evaluate the response of air quality to the reduction of anthropogenic emissions [6]. The effects of COVID-19 lockdown on the changes in air pollutant concentrations were profoundly different. The nitrogen dioxide (NO₂) concentration during COVID-19 was reduced substantially worldwide due to the exceptionally strict traffic controls [7]. The emission of sulfur dioxide (SO₂) is mainly affected by coal-burning enterprises such as steel and petrochemical industry, with SO₂ concentration even showing an increase rather than a decline during COVID-19 period owing to the particularity of the production process [8–11]. A wide range of traffic control measures reduced nitric oxide (NO) emissions substantially and weakened the “titration effect” on ozone (O₃) [12], thus causing a general rise in O₃ concentrations during the COVID-19 pandemic [10,11,13]. As for the source of particulate matter PM₂.₅ (diameter ≤ 2.5 µm) and PM₁₀ (diameter ≤ 10 µm), it includes not only the primary direct emissions from coal combustion, vehicle exhaust, and road dust, but also the secondary aerosols generated by particle conversion, showing some significant regional differences in their response to the lockdown measures [6,14]. Due to the differences in various regions caused by factors such as pollutant emission intensity, meteorological conditions, and atmospheric oxidizability, the improvement of air quality failed to show any consistent spatiotemporal trend between the cities in the same country and in different countries [15]. For example, the highly humid weather in the North China Plain during the COVID-19 pandemic, coupled with the persistent emissions from power plants and the petrochemical industry, still caused serious haze events [6,16].

The different energy structures, industrial compositions, transportation facilities, and meteorological conditions in each region can lead differences in the concentrations of air pollutants to the lockdown measures. The multi-time scale analysis of air pollutant concentrations conducted before and during the COVID-19 periods is conducive to gaining an in-depth understanding the effects of COVID-19 lockdown on air quality and its underlying mechanism. Guiyang, located in Southwest China, is a national big data industry development cluster and an important ecological leisure tourism city. Its special industrial composition has high requirements for excellent air quality. The annual mean concentrations of PM₂.₅, PM₁₀, SO₂, NO₂, O₃, and CO in Guiyang in recent years are (42.53 ± 24.52), (67.56 ± 34.32), (20.78 ± 19.71), (28.32 ± 9.59), (107.59 ± 27.54) µg/m³, and (0.74 ± 0.22) mg/m³, respectively. Except for SO₂ concentration close to or higher than that of cities in central and eastern China, other pollutants are all at a relatively clean level. Although the average level of other air pollutants has been declining, the O₃ concentration on the ground has increased significantly year by year [17]. When solar radiation was relatively high in summer, the concentrations of PM₂.₅ and O₃ were high at the same time, leading to compound pollution [18,19]. It is essential to study the effect of anthropogenic emission reduction on the concentration changes of air pollutants, clarify the process and mechanism of pollution changes, and thus take effective countermeasures to address air pollution. Therefore, Guiyang city was selected in this paper as the study area. On this basis, the concentrations of air pollutant PM₂.₅, PM₁₀, SO₂, NO₂, carbon monoxide (CO), and O₃ with meteorological parameters at different stages before and during the COVID-19 periods in Guiyang city were compared by multiple time scales. Additionally, the effects of COVID-19 lockdown on the changes in air quality in Guiyang city were explored to provide a sensible reference for the formulation of future policies on air pollution control.

2. Materials and Methods

2.1. Regional Overview and Data Sources

Guiyang is situated in the central part of Guizhou Province in the Yunnan-Guizhou Plateau in Southwest China, between 106°07′–107°17′ E and 26°11′–26°55′ N. As of November 2020, Guiyang has a resident population of 497.14 million and an urban population of 378.47 million, with its urbanization rate reaching 76.13%. At present, 10 national control sites dedicated to ambient air monitoring (Figure 1) have been set up in Guiyang city by the China Environmental Monitoring General Station, so as to monitor the concentrations
of air pollutants and the changes in air quality. The method of air quality monitoring is practiced according to the Environmental Quality Standard (GB3095-2012). The monitoring instrument is calibrated regularly according to the Technical Specification for Automatic Monitoring of Environmental Quality (HJ/T193-2005) in order to ensure the accuracy of monitoring data. The data of pollutant concentrations as monitored at each station were published online in real time (http://www.aqistudy.cn/ (accessed on 9 March 2020); http://data.epmap.org/ (accessed on 9 March 2020)). The criteria air pollutants chosen for this study include PM$_{2.5}$, PM$_{10}$, SO$_2$, NO$_2$, CO, and O$_3$. The advantage of using ground-based observational data is that they are more sensitive to the changes in emission sources and more relevant to human exposure and health risks [20]. In addition, meteorological observation data were collected to study the effect of meteorological changes on the concentrations of air pollutants. Meteorological parameters including sunshine duration (SD), temperature (T), wind speed (WS), relative humidity (RH), precipitation (P), and atmospheric pressure (AP) were obtained from the National Basic Meteorological Station of Guiyang City (WMOID = 57816) (http://data.cma.cn/user/toLog in.html/ (accessed on 9 March 2020)).

![Map of Guiyang City](image)

**Figure 1.** Geographical location of Guiyang city and its distribution of air quality stations (based on Google Earth).

### 2.2. The Definition of Lockdown Stage and Research Methods

On 24 January 2020, the Guizhou provincial government decided to initiate the first-level response to public health emergencies. Subsequently, a series of preventative measures were taken in Guiyang, including the closure of all cultural entertainment venues, tourism sites, and other public places; the close-looped management of urban communities; the limit on each household to designate one family member for purchase of daily necessities every 2 days; and the comprehensive implementation of “contactless” distribution of daily necessities at the designated places. On the afternoon of 15 February 2020, Guizhou Province announced that the “checkpoints” between cities, prefectures, counties, and villages would be withdrawn, and the restriction on transportation and circulation would be lifted, marking that the lockdown rating had been lowered. Based on the changes made to the epidemic prevention policy enforced in Guiyang City, the spell from 25 January to 15 February 2020 (22 days in total) is defined as the first-level lockdown period (First-Lockdown), the spell from 3 January to 24 January 2020 (22 days in total) is treated as the pre-lockdown period (Pre-Lockdown), and the spell from 15 February to 8 March 2020 (22 days in total) is regarded as the second-level lockdown (Sec-Lockdown) period. Upon a comparison of the concentration changes in air pollutants at different stages on multiple time scales, meteorological parameters were used to explore the effect of lockdown on the changes in air quality, and to analyze the pollution process. On this basis, targeted countermeasures were proposed for pollution control. Data of pollutant concentrations used in
this paper are all based on hourly concentrations, while the mean mass concentrations on
different time scales were calculated using the data of hourly concentrations, including the
Pre-Lockdown stage, the Fir-Lockdown stage, the Sec-Lockdown stage, day, and hour. The
research methods used in this article include chart description, time series analysis, and
correlation matrix analysis (with Pearson correlation coefficients).

3. Results
3.1. Change Characteristics of the Mean Concentrations of Air Pollutants during the Three Stages

As shown in Figure 2a, the stage changes of PM$_{2.5}$, PM$_{10}$, SO$_2$, NO$_2$, CO, and O$_3$
concentrations were significantly different. As compared with the Pre-Lockdown period,
the mean concentrations of PM$_{10}$, NO$_2$, and CO during the Fir-Lockdown period decreased
by 2.59 μg·m$^{-3}$ (6.67%), 8.41 μg·m$^{-3}$ (45.68%), and 159.09 μg·m$^{-3}$ (18.82%), respectively,
with the mean concentration of NO$_2$ decreasing the most, by nearly 50%. However, the
mean concentration of O$_3$ increased by 18.36 μg·m$^{-3}$ (40.85%), and the mean concentrations
of PM$_{2.5}$ and SO$_2$ changed less significantly or were slightly higher. Compared with the
Fir-Lockdown period, the mean concentrations of PM$_{2.5}$, PM$_{10}$, NO$_2$, and O$_3$ were signifi-
cantly increased during the Sec-Lockdown period, by 7.91 μg·m$^{-3}$ (29.15%), 14.23 μg·m$^{-3}$
(30.27%), 2.91 μg·m$^{-3}$ (29.09%), and 11.23 μg·m$^{-3}$ (17.73%), respectively. In comparison,
the mean concentrations of SO$_2$ and CO dropped slightly. During the Sec-Lockdown period,
there was a significant increase in the concentration of major pollutants due to the lowered
lockdown intensity and human activities such as the resumption of work and production
that increased the emission of pollutants, coupled with the meteorological conditions con-
ducive for pollutants to build up (which we will analyze in Section 4.1). Since SO$_2$ mainly
comes from coal-fired enterprises such as steel and power plants, its production cannot be
interrupted due to the production particularity and process equipment [8]. Therefore, the
mean SO$_2$ concentration increased rather than decreased during the lockdown period.
The most significant source of NOx emission is transportation [7], and the sharp reduction in
NO$_2$ mean concentration during the Fir-Lockdown period is associated with a significant
decrease in vehicle activity caused by strict traffic control. During the Sec-Lockdown pe-
riod, vehicle emissions increased due to the partial resumption of human activities, which
increased the mean concentration of NO$_2$ to some extent (Figure 2a).

Figure 2. (a) Stage mean concentrations of air pollutants before and during the COVID-19 periods
in 2020. (b) Comparison of pollutant concentrations during the Fir-Lockdown period in 2020 with
previous year of 2019, 2018, and 2017. Error bars indicate the standard deviations over multiple days
(2020: the Fir-Lockdown period in 2020; 2019–2017: the same lunar period in 2019, 2018 and 2017
compared with the Fir-Lockdown period in 2020, respectively).

Compared with the same lunar periods in 2019, 2018, and 2017, the mean concentration of NO$_2$
during the Fir-Lockdown period in 2020 decreased by 4.90 μg·m$^{-3}$ (32.92%),
9.54 μg·m$^{-3}$ (48.83%), and 16.27 μg·m$^{-3}$ (61.94%), respectively (Figure 2b), again indicating
that the COVID-19 lockdown was very effective in reducing transportation activities. The lockdown measures had greatly reduced the emission of nitrogen oxides and significantly reduced the NO$_2$ concentration in the air. The NO concentration usually changes synergistically with the NO$_2$ concentration [15]. Decreased NO concentration weakened the “titration effect”, resulting in a significant increase in the O$_3$ concentration by 19.59 µg·m$^{-3}$ (35.5%) during the Fir-Lockdown period in 2020 compared with the same lunar calendar in 2019 [6]. However, the concentration of PM$_{2.5}$, PM$_{10}$, and SO$_2$ did not decrease significantly compared with the previous year—there was even a phenomenon of not decreasing but increasing, which may reflect the influence of other factors on the concentrations of pollutants.

3.2. Change Characteristics of Daily Mean Concentration of Air Pollutants

Meteorological conditions had a significant effect on pollutant concentrations. As shown in Figure 3, the daily concentrations of PM$_{2.5}$, PM$_{10}$, SO$_2$, NO$_2$, CO, and O$_3$ fluctuated significantly and persistently with the changes of meteorological parameters. The peak values of SD and T, as well as the valley values of RH and WS, always coincided with the peak values of various pollutant concentrations. Conversely, the valley values of SD and T, as well as the peak values of RH and WS, always corresponded to the valley values of various pollutant concentrations. It is suggested that long sunshine time, increased temperature, decreased relative humidity and reduced wind speed facilitate pollutants to accumulate, thus causing air pollution. Conversely, it is conducive to the diffusion of pollutants, thus alleviating air pollutions. In addition, the “large” peak value of precipitation corresponded to the valley value of pollutant concentrations, while the “small” peak value corresponded to the peak value of pollutant concentrations (Figure 3e), indicating that the effect of precipitation on pollutant concentrations is more complex. Additionally, large precipitation has a scouring effect on pollutants, which is conducive to the wet deposition of pollutants, while small and medium-sized precipitation will promote the accumulation of pollutants, thereby exacerbating pollution [10].

The stage differences in daily mean concentrations of PM$_{2.5}$, PM$_{10}$, and SO$_2$ are not obvious, while the daily mean concentrations of NO$_2$ and CO decreased to some extent during both Fir-Lockdown and Sec-Lockdown periods, with NO$_2$ concentrations decreasing most significantly during the Fir-Lockdown period (Figure 3c). A wide range of traffic restrictions enforced during the lockdown period was the main reason for the decrease in NO$_2$ concentrations [7], while the decrease in CO concentrations was related to its source contribution composition, its own chemical stability, and the significant reduction in vehicle travel rates [21]. The “titration effect” was reduced by the decrease in NO concentration [12], as a result of which there was a significant rise in O$_3$ concentrations during the Fir-Lockdown period (Figure 3c). In addition, there was a drastic fluctuation in O$_3$ concentrations during the lockdown periods, indicating that photochemical reactions played a crucial role in the change in O$_3$ concentrations. The trend of O$_3$ concentrations was not synchronized with other pollutants, while its peak and valley values did not correspond well to PM$_{2.5}$, PM$_{10}$, SO$_2$, NO$_2$, and CO, indicating that O$_3$, as a secondary pollutant, was also affected by precursor concentrations and photochemical reactions [22].

3.3. Change Characteristics of Hourly Mean Concentrations of Air Pollutants

Figure 4 shows that the diurnal variation curves of PM$_{2.5}$, PM$_{10}$, SO$_2$, NO$_2$, and CO concentrations all conformed to the “bimodal” distribution. The first peak occurred between 10:00 and 13:00, mainly caused by early-morning traffic peaks. NO$_2$ concentration peaked at 10:00, which is the earliest, indicating that the changes in NO$_2$ concentration were most affected by traffic sources. The concentrations of SO$_2$ and CO reached their peak relatively late due to the different sources of pollution than NO$_2$. The first peak characteristics of particulate PM$_{2.5}$ and PM$_{10}$ were not obvious, indicating that early-morning peak traffic emissions contributed insignificantly to particulate matter concentrations. The second peak occurred between 20:00 and 21:00, which was associated with the vertical transfer of
airflow, the accumulation of pollutants caused by the lower height of the boundary layer at night, and the influence of the late peak emission of traffic [23]. Due to the variation in solar radiation and photochemical reactions, the diurnal variation curve of O$_3$ concentration showed a “unimodal” type, which was high during the day and low at night, with the peak appearing at 16:00 in the afternoon.

![Figure 3. Daily mean pollutant concentrations and meteorological parameters from 3 January 2020 to 8 March 2020 in Guiyang city. (a) PM$_{2.5}$/PM$_{10}$, (b) SO$_2$, CO, (c) NO$_2$, O$_3$, (d) T: temperature, RH: relative humidity, (e) SD: sunshine duration, P: precipitation, (f) WS: wind speed.](image)

The hourly mean concentration of PM$_{2.5}$ during the Fir-Lockdown period was comparable with that during the Pre-Lockdown period, but the hourly mean concentration of PM$_{10}$ in the daytime (11:00–20:00) during the Fir-Lockdown period was significantly lower. These results show that COVID-19 lockdown significantly reduced the PM$_{10}$ concentration during the day, but had little effect on the PM$_{10}$ concentration at night, and it had little effect on the change of PM$_{2.5}$ concentration throughout the day. The differences in the diurnal variation characteristics of SO$_2$ concentrations across the three stages were insignificant, reflecting the marginal effect of lockdown on SO$_2$ concentrations. Unlike PM$_{2.5}$, the con-
concentrations of PM$_{10}$, SO$_2$, NO$_2$, CO during lockdown periods were significantly lower than in the Pre-Lockdown period, indicating that they were most affected by lockdown. During the Fir-Lockdown period, the peak characteristics of NO$_2$ and CO concentrations were clearly inconspicuous, which is related to the fact that there were barely any commuting traffic peaks appearing during the strict control period of COVID-19. Due to the decrease in NO concentrations, the “titration effect” diminished and the O$_3$ concentrations rose significantly during lockdown periods (Figure 4f,i).

![Graphs showing diurnal variation of pollutants](image)

**Figure 4.** Hourly mean values of air pollutants and its ratios in a day during the Pre-Lockdown, Fir-Lockdown, and Sec-Lockdown stage. (a) PM$_{2.5}$, (b) PM$_{10}$, (c) SO$_2$, (d) NO$_2$, (e) CO, (f) O$_3$, (g) O$_x$, (h) PM$_{2.5}$/CO, (i) NO$_2$/O$_3$.

### 4. Discussion
#### 4.1. Effect of Meteorological Conditions on Air Pollutant Concentrations

The mean concentrations of PM$_{2.5}$ and PM$_{10}$ during the Sec-Lockdown period were significantly higher compared with those during the Pre-Lockdown period (Figure 2a). According to the diurnal variation results, the hourly mean concentrations of PM$_{2.5}$ and PM$_{10}$ during the Sec-Lockdown period were significantly higher compared with those during the previous two periods (Figure 4a,b), and the increase in particulate matter concentrations occurred during the Sec-Lockdown period under the conditions of reduced emissions as compared with those during the Pre-Lockdown period. In addition, during the Sec-Lockdown period, the levels of vehicle activity increased the concentrations of ambient NO$_2$ (Figure 4d) due to the resumption of production, thereby increasing the “titration” consumption of O$_3$ [12]. However, the O$_3$ concentration increased significantly (Figures 2 and 4f). Obviously, anthropogenic emission alone is inadequate to explain the above phenomena. Photochemical oxidation processes, sulfate–nitrate–ammonium systems, plus PM$_{2.5}$ secondary generation also had an important contribution to the increased concentrations of particulate matter and O$_3$ during the Sec-Lockdown period [24,25]. Figure 4f shows that the hourly mean concentration of O$_3$ increased synchronously at all times during the Fir-Lockdown period compared with that during the Pre-Lockdown period. However, the hourly mean concentration of O$_3$ increased significantly only in the daytime (11:00–20:00: photochemical reaction period) during the Sec-Lockdown period, the O$_3$ concentration showed no significant variations at night. It is obvious that the increase in O$_3$ concentration during the Fir-Lockdown period was mainly attributed to the decrease...
in NO concentration and the diminishing “titration effect”. In comparison, the increase in O₃ concentration during the Sec-Lockdown period was more affected by photochemical reaction dominated by meteorological conditions [22].

The meteorological condition has significantly different effects on the changes in the concentrations of various air pollutants. Table 1 shows the relationship between daily mean concentrations of air pollutants and meteorological parameters from 3 January 2020 to 8 March 2020 in Guiyang city. Among them, the Pearson correlation coefficients of O₃ and T, RH, and SD were 0.51, −0.77, and 0.58, respectively. The correlation coefficients were the largest, indicating that temperature, relative humidity, and sunshine hours had a significant effect on the change in O₃ concentration. Temperature and sunshine hours were positively correlated with O₃ concentration, and relative humidity was inversely correlated with O₃ concentration, indicating that the longer the sunshine time, the higher the temperature and the lower the relative humidity, which was more conducive to the photochemical reaction to produce O₃. The Pearson correlation coefficients of relative humidity and wind speed with SO₂ were −0.58 and −0.51, respectively, showing a moderate negative correlation, which may indicate that small winds and high humidity weather was not conducive to the diffusion of SO₂. In addition, T, RH, WS, SD, P, PM₂.₅, and PM₁₀ also showed a certain degree of correlation, which comprehensively reflected the effects of diffusion and secondary generation of particulate pollutants. The Pearson correlation coefficients between the remaining meteorological parameters and the pollutant concentrations were relatively small, indicating that they had little effect on changes in air quality.

Table 1. Pearson correlation coefficients between daily mean concentrations of air pollutants and meteorological parameters from 3 January 2020 to 8 March 2020 in Guiyang city (T: temperature, SD: sunshine duration, WS: wind speed, RH: relative humidity, P: precipitation, AP: atmospheric pressure).

| Pollutant Item | T   | RH  | WS  | SD  | P   | AP  |
|---------------|-----|-----|-----|-----|-----|-----|
| PM₂.₅        | 0.29| −0.36| −0.35| 0.17| −0.33| −0.05|
| PM₁₀         | 0.41| −0.42| −0.30| 0.25| −0.36| −0.12|
| SO₂          | −0.02| −0.58| −0.51| 0.38| −0.24| 0.09|
| CO           | −0.23| 0.41| −0.30| −0.23| −0.11| −0.12|
| NO₂          | 0.19| −0.01| −0.22| 0.17| −0.15| −0.34|
| O₃           | 0.51| −0.77| 0.04| 0.58| −0.15| −0.16|

Note: The confidence levels are all α = 0.01 (two-sided test).

We compared the mean meteorological conditions of the three stages before and after the lockdown in 2020. The results show that the mean temperature and sunshine hours increased significantly, the relative humidity and precipitation decreased significantly, and the wind speed varied insignificantly during the Sec-Lockdown period compared with those during the previous stages (Figure 5a). It is evident that the meteorological conditions during the Sec-Lockdown period are more conducive to the occurrence of photochemical reaction, thus generating more O₃ to increase its concentration in the air. In addition, due to the increase in sunshine hours during the Sec-Lockdown period, the temperature rose, the surface became too dry, and the dust on the surface was more likely to rise into the air, thus increasing the concentration of coarse particulate matter PM₁₀ in the air (Figure 4b).

4.2. Generation of Secondary Aerosols and Its Impact on Air Quality

The diurnal variation of PM₂.₅ concentration during the Fir-Lockdown period was basically consistent with that during the Pre-Lockdown period, while the hourly concentration of PM₁₀ decreased to some extent in the daytime (12:00–21:00) during the Fir-Lockdown period compared with the Pre-Lockdown period (Figure 4a,b), indicating that there are other potential sources of PM₂.₅ in the daytime during the Fir-Lockdown period to compensate for the reduction in emissions. The different degrees of variation in PM₂.₅ and PM₁₀ concentrations before and after lockdown suggested that pollution variations cannot be fully explained by primary emissions, as the secondary aerosols generated by gas–particle transitions play an equally crucial role in the pollution process [26].
During the Sec-Lockdown period, meteorological conditions facilitated photochemical reactions to generate O₃, thus increasing O₃ concentrations (Figure 4f) and enhancing atmospheric oxidizing Oₓ (Figure 4g). This is conducive to the secondary aerosols generated by gas–particle transitions, thus compensating for the reduced primary emission of PM₂.₅ [15]. PM₂.₅/CO is an effective indicator of the intensity of secondary aerosols generated, the value of which represents the efficiency of secondary aerosols generation [27]. The PM₂.₅/CO ratio was higher during the Sec-Lockdown period than that during the previous two stages (Figure 4h), indicating that the secondary generation of aerosols during the Sec-Lockdown period may contribute significantly to the high concentrations of PM₂.₅. As revealed by the analysis of the average particle number size distribution and chemical mass fraction of PM₂.₅ before and after the Spring Festival in Beijing, the generation of secondary aerosols during the Spring Festival offset the reduction in regional PM₂.₅ concentrations [27], which is consistent with our research records.

Figure 5. (a) Comparison of mean meteorological parameters during the Pre-Lockdown, Fir-Lockdown, and Sec-Lockdown stage, error bars indicate the standard deviations over multiple days. (b–d) Correlation heat map among daily mean concentrations of pollutants during the Pre-Lockdown, Fir-Lockdown and Sec-Lockdown period, respectively.

During the Pre-Lockdown period, the Pearson correlation coefficient between O₃ and PM₂.₅ was 0.12 (Figure 5b), which was relatively weak. However, the Pearson correlation coefficients between O₃ and PM₂.₅ during the first- and second-level lockdown periods were 0.52 and 0.44, respectively (Figure 5c,d), both showing a moderately positive correlation. The correlation difference before and during the lockdown periods reflects that the PM₂.₅ concentrations were significantly affected by the changes in the O₃ concentration during the two lockdown periods, which may indicate that the O₃ has increased the atmospheric oxidation, which in turn facilitated the conversion of gas to particulate matter to generate secondary aerosols. It has been pointed out in some prior studies that SO₂ and NOx can be oxidized to generate sulfate and nitrate, respectively, through a variety of chemical pathways. Additionally, the secondary inorganic compounds in particulate matter are usually dominated by sulfate and nitrate [28–30]. The secondary aerosol formation of sulfate...
and nitrate is often the primary cause of the sharp rise in the PM$_{2.5}$ concentrations [31]. During the Fir-Lockdown period, NO$_2$ concentrations decreased substantially, while PM$_{2.5}$ concentrations remained the same as the Pre-lockdown period, which may be attributed to SO$_2$ reacting with OH radicals to generate more sulfate aerosols [32], thus replacing nitrate aerosols. Therefore, the PM$_{2.5}$ concentration did not change much during the Fir-Lockdown period. During the Pre-Lockdown period, the Pearson correlation coefficient between SO$_2$ and PM$_{2.5}$ was 0.82 (Figure 5b), which was relatively strong. However, the Pearson correlation coefficients between SO$_2$ and PM$_{2.5}$ during the first and second level lockdown periods were 0.51 and 0.30, respectively (Figure 5c,d). The correlation degree between SO$_2$ and PM$_{2.5}$ decreased significantly, which may indicate that SO$_2$ was more consumed to generate more sulfate aerosols during the two lockdown periods. The newly generated secondary aerosols are usually small in particle size and have almost no effect on the changes in PM$_{10}$ concentration. Therefore, the PM$_{10}$ concentration was low in the daytime during the Fir-Lockdown period. Sun et al. [33] conducted a study on the effect of lockdown on PM concentration and composition in Beijing, China, and obtained the results suggesting that the main varieties of PM associated with traffic, cooking, and coal-burning emissions were reduced by an average of 30–50% during the lockdown period. However, secondary inorganic aerosol (SIA) and secondary organic aerosol (SOA) increased by 60–110% and 52–175%, respectively, due to the enhanced regional delivery of air masses and generation of secondary aerosol.

4.3. Policy Implications for Quality Prevention and Control

Policy decisions are the most effective solution to reducing the emission of air pollutants and improving air quality, which is beneficial to human health and the environment. However, the emission reduction alone contributes only to reducing the primary pollutants in the air. Additionally, the chemical process of the atmosphere can be changed. Anthropogenic emission reduction would reduce NO concentration and diminish the "titration effect", thus increasing O$_3$ concentrations. Alternatively, the enhancement of atmospheric oxidizability would promote the generation of secondary aerosols through gas–particle conversion, thus compensating for the reduction in PM$_{2.5}$ concentrations. Therefore, it is practically significant to develop appropriate air pollution control policies for suppressing the secondary generation of both PM$_{2.5}$ and O$_3$.

4.4. Existing Problems and Deficiencies

In this paper, we discussed only the effect caused by the generation of secondary aerosols on the concentration of various pollutants according to the characteristics of multi-time scale changes in air pollutant concentrations, the changes in atmospheric oxidizability at each stage, and the values of PM$_{2.5}$/CO. However, there is a lack of understanding as to the generation of secondary aerosols and mechanisms of gas–particle conversion. Therefore, it is necessary to further observe the practical changes in the chemical composition of PM$_{2.5}$ before and after lockdown, which will serve as a supplement to the research conducted in the future.

5. Conclusions

The effects of COVID-19 lockdown on the changes in concentrations of criteria air pollutants were significantly different. Compared with the Pre-Lockdown period, the mean concentrations of PM$_{10}$, NO$_2$, and CO decreased during the Fir-Lockdown period by 2.59 µg m$^{-3}$ (6.67%), 8.41 µg m$^{-3}$ (45.68%), and 159.09 µg m$^{-3}$ (18.82%), respectively. Due to the decrease in NO concentration and the weakening of "titration effect", the mean concentration of O$_3$ increased by 18.36 µg m$^{-3}$ (40.85%) compared with the Pre-Lockdown period. The mean concentration of PM$_{2.5}$ and SO$_2$ was slightly higher than that of the Pre-Lockdown period. Meteorological conditions had a significant effect on the pollutant concentrations, while the daily mean concentrations of PM$_{2.5}$, PM$_{10}$, SO$_2$, NO$_2$, CO, and O$_3$ varied significantly with meteorological parameters in Guiyang city. The reduction
in the lockdown level, the resumption of production, and other human activities have increased anthropogenic emissions, and the meteorological conditions are conducive to the formation of O₃ by photochemical reactions and the accumulation of pollutants, resulting in the concentration of main pollutants PM₂.₅, PM₁₀, and O₃ increasing significantly during the Sec-Lockdown period. O₃ concentrations increased and atmospheric oxidizability enhanced during the lockdown period, which is favorable to the generation of secondary aerosols by means of gas–particle transitions, thus compensating for the reduced PM₂.₅ concentrations. These results suggest the necessity to initiate appropriate policies on air pollution control while suppressing the secondary generation of both PM₂.₅ and O₃.

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