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The impact of COVID-19 lockdown on atmospheric CO₂ in Xi’an, China

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A B S T R A C T

Lockdown measures to control the spread of the novel coronavirus disease (COVID-19) sharply limited energy consumption and carbon emissions. The lockdown effect on carbon emissions has been studied by many researchers using statistical approaches. However, the lockdown effect on atmospheric carbon dioxide (CO₂) on an urban scale remains unclear. Here we present CO₂ concentration and carbon isotopic (δ¹³C) measurements to assess the impact of COVID-19 control measures on atmospheric CO₂ in Xi’an, China. We find that CO₂ concentrations during the lockdown period were 7.5% lower than during the normal period (prior to the Spring Festival, Jan 25 to Feb 4, 2020). The observed CO₂ discrepancy (total CO₂ minus background CO₂) during the lockdown period was 52.3% lower than that during the normal period, and 35.7% lower than the estimated CO₂ discrepancy with the effect of weather removed. A Keeling plot shows that in contrast CO₂ concentrations and δ¹³C were weakly correlated (R² = 0.18) during the lockdown period, reflecting a change in CO₂ sources imposed by the curtailment of traffic and industrial emissions. Our study also shows that the sharp reduction in atmospheric CO₂ during lockdown were short-lived, and returned to normal levels within months after lockdown measures were lifted.

1. Introduction

The novel coronavirus disease (COVID-19) epidemic is a major public health emergency, which spread fast, caused extensive infections and proved difficult to contain. In order to block the spread of COVID-19 and protect people’s health, the Chinese government adopted strong lockdown measures in Wuhan on January 23, 2020. In the next few days, a number of provinces and cities across the country also began to adopt similar measures to control the spread of the disease. These included strict traffic controls, restrictions on residents’ going out, and closures of market gatherings and various businesses. The reopening of schools in China following the Spring Festival (Jan 25 to Feb 4, 2020) was also delayed. Only business entities that provided people with daily necessities, such as health care and food supplies, remained open. As a result of these COVID-19 prevention measures, the number of vehicles on the road declined dramatically and manufacturing production dropped sharply (Wang et al., 2020a).

Fossil fuel combustion produces both carbon dioxide (CO₂) emissions and air pollutants. Energy consumption (including fossil fuels) has increased sharply in recent years as a result of urbanization and modern lifestyle changes (Hosseini et al., 2019). Fossil fuels are responsible for 85% of CO₂ emissions and 64% of total greenhouse gas emissions (Razzag et al., 2020). As a consequence of increasing energy consumption, CO₂-dominated greenhouse gases have also increased in recent years (Adeniyi et al., 2019), and on a global scale are attributed to the following sectors: electricity and heat generation (44%), transportation (26%), and industry (19%), according to the International Energy Agency (IEA, 2020). The consumption of fossil fuels causes ecological and environmental problems (Al-Juboori et al., 2020a), such as climate warming and urban smog (Sher et al., 2020). CO₂ emissions must be curtailed to mitigate global warming and enhance sustainable development (Lelieveld et al., 2019). This strategy hinges on alternative energy technologies, which include: solar and wind power (Qazi et al., 2019); sustainable hydrocarbon fuel production from CO₂ (Al-Juboori

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et al., 2020b); hydrogen fuel cells (Al-Shara et al., 2019); and biofuels (Razzaq et al., 2020). Additionally, carbon capture and sequestration techniques such as post-combustion CO_2 capture using fast adsorbents derived from biomass (Sher et al., 2020) can reduce CO_2 emissions. The transition from fossil fuels to renewable energy will play an essential role in CO_2 emissions reduction, but it is not happening fast enough (Gielen et al., 2019). The COVID-19 pandemic provided an opportunity to test how fast carbon emissions can be reduced by sharply curtailing emissions.

Control measures to check the spread of COVID-19 led to a reduction in road and air traffic, a temporary closure of businesses, and a decrease in industrial productivity (Ding et al., 2020). A number of factors that contributed to CO_2 emissions reductions (Wang et al., 2020b) include: 1) reduced power demands due to the delayed resumption of work after the Spring Festival; 2) a reduced demand for steel and blast furnace operation time; 3) a reduced energy demand from a variety of business enterprises; and 4) COVID-19 restrictions required people to stay at home. This latter factor markedly reduced road and air traffic, with immediate reductions in transportation-related CO_2 emissions. Several studies have performed statistical analyses to estimate national and global reductions in carbon emissions that resulted from pandemic prevention measures. For example, compared with data from the same time periods in 2019, daily global CO_2 emissions decreased by 17.0% by early April 2020 (Le Quéré et al., 2020) and decreased by 8.8% in the first half of 2020 (Liu et al., 2020a). In China, carbon emissions fell by 11.0% over the first quarter of 2019 (Han et al., 2020). There are also a number of observational studies that shows declines of atmospheric pollutants. Bauwens et al. (2020) found that NO_2 concentrations decreased rapidly following the COVID-19 lockdown both in China and Italy. Xu et al. (2020) reported that submicron aerosol mass concentrations were reduced by 50% during the COVID-19 lockdown in Lanzhou, China. Surface measurements made at more than 800 monitoring stations show that mean levels of PM_{2.5} and NO_2 in northern China decreased by approximately 35% and 60%, respectively, after the COVID-19 lockdown (Shi and Brasseur, 2020). Sharma et al. (2020) reported that a PM_{2.5} concentration decrease of 43% in India during the COVID-19 lockdown period compared to the previous 4 years.

Cities play an important role in the effort to reduce carbon emissions (Xu et al., 2021), as they account for about 70% of global carbon emissions (Churkina, 2016). The COVID-19 pandemic represents an experiment that can be used to test how much urban-scale atmospheric CO_2 concentrations are lowered when anthropogenic CO_2 emissions are sharply curtailed. Liu et al. (2020b) reported decreases in on-road CO_2 concentrations in Beijing during COVID-19 with six on-road observations using mobile platforms. Turner et al. (2020) observed a 5–50 ppm decrease in midweek CO_2 concentrations during rush hour monitoring in the San Francisco Bay Area. However, the response of averaged atmospheric CO_2 concentration to the lockdown on an urban scale is still unknown (Pigliautile et al., 2020).

Xi’an is the largest city in northwestern China and all of its residential complexes were locked down from February 5 to February 21, 2020, due to COVID-19 control measures. Here we study the urban-scale effect of the lockdown in Xi’an on atmospheric CO_2 concentrations and stable carbon isotope compositions (δ^{13}C) in the first quarter of 2020. The objective of this study is to detect the averaged CO_2 concentration change during the 2020 COVID-19 lockdown period relative to 2019 levels and relative to meteorological corrected levels. Quantifying the impact of the COVID-19 lockdown on atmospheric CO_2 concentrations on a city scale is important to future carbon emission measures for sustainable development. It can also provide useful information for modeling studies.

2. Methods

2.1. Study site

Xi’an is currently the capital of Shaanxi Province and in historical times, was the capital of China during thirteen dynasties. Its population reached 10 million in 2018. Xi’an is located in the south-central part of the Guanzhong Basin, bordered by the loess plateau to the north and the Qinling Mountains to the south. This basinal configuration, and the mild winds typical of Xi’an most of the year, inhibit the removal of air pollutants (Yang, 2003). The observations made for this study (Fig. 1) were carried out on the main building of the Institute of Earth Environment, Chinese Academy of Sciences (IEECAS) in southeast Xi’an from Jan 1 to March 31, 2019 and 2020.

2.2. Timeline of COVID-19 responses in Xi’an during the study period

We divided the first quarter of 2020 into five stages according to the different measures taken in response to COVID-19. Stage 1 (January 1 to January 24, 2020) represents a normal period before the Spring Festival holiday (the Chinese Lunar New Year). Stage 2 (January 25 to February 4) is during the Spring Festival holiday of 2020. Spring Festival is the largest holiday in China. In normal years, people travel to visit their relatives and friends from the first day of the Chinese New Year. But in 2020, millions of people were asked to stay at home in an effort to stop the spread of the new coronavirus. Stage 3 (February 5 to February 21) was the lockdown period, with the strictest control measures enforced. Only one person per family was allowed to venture out to purchase daily necessities such as food and medicine, once every two days. The reopening of industries and schools in Xi’an was also delayed throughout this period. Transportation was largely restricted with few vehicles on the road during that time. Stage 4 (February 22 to February 28) was a transition period as the lockdown measures were relaxed. Businesses began to reopen and restrictions on residents began to be lifted. During stage 5 (February 29 to March 31) normal patterns were reestablished, approaching Stage 1 conditions. However, schools and cinemas did not reopen immediately, and group tours that crossed provincial borders were still restricted.

2.3. Experimental set-up

Atmospheric CO_2 concentration and its δ^{13}C were measured using a Picarro G2131-i carbon isotopic analyzer (Picarro, Inc., USA). The Picarro analyzer measures CO_2 concentration, δ^{13}C in CO_2, CH_4 and H_2O. The precision for CO_2 is better than 0.2 ppm and for δ^{13}C is better than 0.2%. Air samples were pumped directly into the Picarro analyzer at a flow rate of 25 ml/min. The CO_2 concentration was derived from the sum of dry air concentrations of \textsuperscript{12}CO_2 and \textsuperscript{13}CO_2. The instrument was calibrated by two standard gases (cylinder 1 with CO_2 395.49 ± 0.02 ppm, δ^{13}C in CO_2 −8.980 ± 0.008‰, CH_4 1993.5 ± 0.2 ppb, and cylinder 2 with CO_2 491.43 ± 0.02 ppm, δ^{13}C in CO_2 −10.395 ± 0.024‰, CH_4 3029.3 ± 0.5 ppb) obtained from the Chinese Academy of Meteorological Sciences. Each standard gas is pressurized in a 29.5-L treated aluminum alloy cylinder (Scott-Marrin, Inc., California) fitted with a high-purity, two-stage gas regulator, and calibrated with cylinders assigned by the WMO/GAW CO_2 Central Calibration Laboratory operated by NOAA/ESRL.

2.4. Reconstruction of missing CO_2 data

To study the atmospheric CO_2 response to the lockdown, we took January to March 2019, as a reference period. However, 6 days during the period (January 27 to February 1, 2019) were missing due to instrument failure. A study in Shanghai, China found that atmospheric CO_2 and CO correlate well with each other (Wei et al., 2020). Daily averaged CO data for Xi’an were obtained from the Chinese Air Quality...
online Monitoring and Analysis Platform (CAQMAP, 2020), and we found that the daily averaged CO₂ and CO have a highly significant (p < 0.001) linear relationship (Fig. 2). Based on this, we reconstructed the daily average CO₂ concentrations to fill the gap from the 6 missing days in our record.

3. Results and discussion

3.1. Analysis of the atmospheric CO₂ concentration in Xi’an

Daily CO₂ concentration variations in the first quarters of 2019 and 2020 are shown in Fig. 3. CO₂ concentrations decreased during the 2020 Spring Festival because the Xi’an city government began to limit outdoor activities from the beginning of the Chinese New Year. The Spring Festival trend in 2020 is much different from the typical pattern represented by the 2019 data. In the latter, CO₂ concentration began to increase since the first day of the holiday as people started to travel to visit relatives and friends. This resulted in the enhancement of vehicle emissions. In 2020, CO₂ concentrations decreased steadily from the start of the Spring Festival to the end of the lockdown. In the transition period, CO₂ concentrations followed an increasing trend, as lockdown measures in Xi’an were relaxed and people returned to work. After the reestablished normal period in the city, CO₂ concentrations became stable, with weak daily fluctuations.

The red dotted line in Fig. 3(b) shows the atmospheric CO₂ concentrations in the five stages in 2020: 1) 484.5 ± 21.4 ppm, 2) 458.6 ± 12.9 ppm, 3) 448.0 ± 15.7 ppm, 4) 456.1 ± 9.8 ppm and 5) 442.4 ± 9.6 ppm. This trend correlates well with the timing of measures taken to control the spread of COVID-19. The CO₂ concentration in the lockdown period is significantly lower (p < 0.001) than that in the normal period before the Spring Festival by 7.5% and is also lower (p = 0.083) than the Spring Festival period and lower (p = 0.235) than the transition period.

Because the natural variability of CO₂ caused by the carbon cycle (Peters et al., 2017) and meteorological conditions (Ballantyne et al., 2012) in the short term are large, they may mask anthropogenic variability. Hence, we used monthly-averaged CO₂ concentrations to check whether an anomaly could be distinguished in February (the height of the lockdown). The horizontal black dashed lines in Fig. 3 show the monthly average CO₂ concentrations. The values are 479.2 ± 21.9 ppm, 451.0 ± 14.2 ppm, and 442.0 ± 9.4 ppm for January, February and March.

Fig. 1. The location of the study site (IEECAS) in Xi’an.

Fig. 2. Linear regressions between CO₂ and CO for the first quarter of 2019 (a) and 2020 (b) in Xi’an. The CO data are from CAQMAP (2020).
March 2020, respectively; and as a reference they are 472.5 ± 20.9 ppm, 457.3 ± 16.2 ppm, and 439.8.0 ± 10.1 ppm for January, February and March 2019, respectively. In January and March the CO₂ concentrations are slightly higher in 2020 than that in 2019, but in February, CO₂ concentrations are significantly (p < 0.01) lower (1.4% or 6.3 ppm) in 2020 than in 2019. The changes in monthly average CO₂ concentrations were the same for the first quarters of 2019 and 2020, which decreased in February (as compared to January) and decreased again in March (as compared to February). CO₂ declines in March were significant in both 2019 (p < 0.01) and 2020 (p < 0.01). The decrease in February compared with January is not significant in 2019 (p = 0.108), while it is significant in 2020 (p < 0.01), suggesting that the lockdown influenced fossil fuel CO₂ emissions. The CO₂ concentration declined 3.2% (or 15.2 ppm) in February compared with January in 2019, but in 2020 it declined 5.9% (or 28.2 ppm). These all indicate the influence of the lockdown on CO₂ concentrations.

3.2. Prediction of CO₂ from meteorological data

Although the comparison of the five stages in the first quarter of 2020, and the month-to-month comparison between 2020 and 2019 show an apparent influence of COVID-19 measures, these results include both natural carbon cycle variability and meteorological conditions. Quantifying and attributing changes in CO₂ concentrations requires accounting for meteorological effects in addition to direct emissions (Turner et al., 2020). We did this by determining the difference between CO₂ excess-est and CO₂ excess-obs, as explained next.

We adopted the method of Venter et al. (2020), that predicts air pollution proxies (PM₂.₅, O₃, and NO₂) from meteorological parameters, to estimate first quarter 2020 CO₂ concentrations (CO₂ est). We first established the relationship between daily CO₂ concentration and weather parameters (temperature, relative humidity, wind speed and precipitation, at Xi’an Jinghe National Meteorological Station, No. 57131, RPS, 2020) in 2019 using a multiple linear regression model. The resulting R² and p-value for the relationship are 0.573 and < 0.001, respectively. The regression equation we derived is as follows:

\[ CO₂ = 456.729–1.6T +0.313\cdot RH–0.829\cdot PP–1.88\cdot WS \]  

with the parameters T (temperature, °C), RH (relative humidity, %), PP (precipitation, mm) and WS (wind speed, m/s). Then the daily CO₂ concentrations in the first quarter of 2020 were estimated by inputting the daily meteorological parameters of 2020. Considering the background CO₂ concentration, the difference between the observed CO₂ obsexcess (observed CO₂ concentration minus the background CO₂ concentration from Mauna Loa, Hawaii, NOAA, 2020), and the estimated CO₂ est-excess (estimated CO₂ concentration minus the background CO₂ concentration) is defined as the lockdown effect. In fact, the CO₂ excess includes fossil fuel CO₂ (CO₂ff) and biogenic CO₂ (CO₂ bio) (Levin et al., 2003). Former studies in Xi’an showed that in winter months, the CO₂ excess comes predominately from fossil fuel emissions (Wang et al., 2018), which can account for more than 90% (Zhou et al., 2020). Thus the CO₂ excess in our study mainly reflects fossil fuel CO₂ variations.

Fig. 4 shows that the CO₂ excess-obs is significantly (p = 0.013) lower than the CO₂ excess-est by 35.7% (or 11.7 ppm) during the lockdown period, which is close to the reduction of fossil fuel emissions in China, by 32.0 ± 12% in February 2020 (Tohjima et al., 2020). However, during the normal period before the Spring Festival the CO₂ excess-obs is significantly (p = 0.005) higher than the CO₂ excess-est by 24.0% (or 13.8 ppm). In the other three stages there are no obvious differences between the observed and estimated values. This result indicates a clear COVID-19 lockdown effect on CO₂. The CO₂ excess-est during the lockdown period is 20.4% lower than that during the normal period before the

![Fig. 3. Atmospheric CO₂ concentration in Xi’an City in the first quarter of 2019 (a) and 2020 (b). The blue line shows daily average CO₂ concentrations; black dashed line shows monthly average CO₂ concentrations; the red dotted line in Fig. 3(b) shows average CO₂ concentrations in each stage. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)](image-url)
Spring Festival. Note that the amplitude of this decline is significantly smaller than the uncorrected $\mathrm{CO}_2$ excess-obs value, which declined 52.3%.

In the study of Liu et al. (2020b), a higher $\mathrm{CO}_2$ concentration was observed during the lockdown period in 2020 than the same period in 2019. This higher $\mathrm{CO}_2$ should be attributed to the weather conditions, rather than COVID-19 control measures since they observed a significant decline of on-road $\mathrm{CO}_2$ concentration for the same period. In the transition period the $\mathrm{CO}_2$ excess-obs concentration was higher ($p = 0.738$) than $\mathrm{CO}_2$ excess-est again, indicating a return to pre-lockdown conditions.

The variation of atmospheric $\mathrm{CO}_2$ excess concentrations in the first quarter of 2020 indicates that quickly lowering atmospheric $\mathrm{CO}_2$ concentrations is possible. However, the impact of the COVID-19 lockdown measures on atmospheric $\mathrm{CO}_2$ concentrations is short-term. To maintain low atmospheric $\mathrm{CO}_2$ concentrations, emissions must continue to be suppressed, perhaps through green technologies to produce hydrogen (Al-Shara et al., 2021) and hydrogen fuel cells (Khzouz et al., 2020).

### 3.3. Evidence of the COVID-19 lockdown effect on $\mathrm{CO}_2$ from isotopic measurements

Stable isotopes ($\delta^{13}\mathrm{C}$) in atmospheric $\mathrm{CO}_2$ provide a valuable means to distinguish between different $\mathrm{CO}_2$ sources in air because different sources can have very different $\delta^{13}\mathrm{C}$ values. In order to investigate whether $\mathrm{CO}_2$ sources changed significantly during the lockdown period, the Keeling-plot method (Keeling, 1958) was used to determine $\delta^{13}\mathrm{C}$ values for each time period. The observed $\mathrm{CO}_2$ can be divided into background $\mathrm{CO}_2$ and source $\mathrm{CO}_2$. According to the mass balance of $\mathrm{CO}_2$ and its stable carbon isotopes, we can write the following (Keeling, 1958):

\[
\delta^{13}\mathrm{C}_\text{obs} = \delta^{13}\mathrm{C}_\text{bg} + \delta^{13}\mathrm{C}_\text{excess} 
\]

\[
\delta^{13}\mathrm{C}_\text{obs} = \delta^{13}\mathrm{C}_\text{bg} + \delta^{13}\mathrm{C}_\text{excess} 
\]

Combining equations (2) and (3) we can obtain:

\[
\delta^{13}\mathrm{C}_\text{obs} = \frac{\delta^{13}\mathrm{C}_\text{bg} - \delta^{13}\mathrm{C}_\text{excess}}{1 - \frac{\delta^{13}\mathrm{C}_\text{bg}}{\delta^{13}\mathrm{C}_\text{obs}}} + \delta^{13}\mathrm{C}_\text{excess} 
\]
By plotting δ^{13}C_{obs} and 1/CO_{2,obs}, the mean isotopic signature of the CO2 excess can be obtained as the y intercept of the Keeling-plot curve. We applied this method to the morning rush hour for each period we divided 2020 to study the effect of lockdown on vehicle emissions (Fig. 5).

The results show that the δ^{13}C_{excess} values for the normal period before Spring Festival, during Spring Festival, during the lockdown period, in the transition period, and the reestablished normal period are: 26.8‰, −25.6‰, −17.5‰, −27.3‰, and −24.9‰, respectively. The δ^{13}C_{excess} in the lockdown period is obviously different from the other four stages. We note that the very low R² value (0.18) for the lockdown period makes it impossible for us to obtain a reliable δ^{13}C_{source} value. The Keeling plot method assumes the background and source are constant during the period investigated (Keeling, 1958). The CO2 concentrations and associated δ^{13}C show negligible variations at the background site in Mauna Loa (NOAA, 2020), thus a low R² might result from the low CO2 range (Zobitz et al., 2006), which is only 41.6 ppm in the lockdown (before the Spring Festival). Daily CO2 advection of different air masses or changes in the CO2 sources during the winter season.

4. Conclusions

The impact of the COVID-19 lockdown on atmospheric CO2 concentrations in Xi’an was assessed using ground observations corrected for the influence of weather. The results show that during the lockdown period observed CO2 concentrations were 7.5% lower than normal (before the Spring Festival). Daily CO2 sources changed during the lockdown, as reflected by the low correlation (R² value) observed using the Keeling-plot method applied before, during, and after the lockdown period. Although the impact of the lockdown on atmospheric CO2 concentration in Xi’an was large, its impact was short-lived. Following the relaxation of the pandemic prevention measures, CO2 concentrations increased again to similar levels as observed in 2019. This study quantifies to some extent the rate and magnitude of changes that can occur by sharply curtailing anthropogenic CO2 emissions in an urban environment. In practice, we expect that such reductions can be achieved through the implementation of green technologies. Our monitoring approach can be used in the future to assess the efficacy of such technologies.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envres.2021.111208.

Credit author statement

Shugang Wu, designed research. Shugang Wu and Weijian Zhou performed research; Shugang Wu, Weijian Zhou and Xiaohu Xiong analyzed data; and Shugang Wu, Weijian Zhou, Xiaohu Xiong, G. S. Burr, Peng Cheng, Peng Wang, Zhenchuan Niu, Yaoyao Hou wrote the paper.

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