Observed decreases in on-road CO_2 concentrations in Beijing during COVID-19 ~~restrictions~~

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Abstract:

To prevent the spread of the COVID-19 epidemic, restrictions such as "lockdowns", were conducted globally, which led to a significant reduction in fossil fuel emissions, especially in urban ~~regions~~areas. However, CO_2 concentrations in urban ~~regions~~ areas are affected by many factors, such as weather, biological sinks and background CO_2 fluctuations. Thus, it is difficult to directly observe the CO_2 reductions ~~in CO2 concentrations with~~ from sparse ground observations. Here, we focus on urban ground transportation emissions, which were dramatically affected by the ~~prohibitions~~restrictions, to determine the reduction signals. We conducted six series of on-road CO_2 observations in Beijing using mobile platforms before (BC), during (DC) and after ~~COVID-19 prohibitions~~ (AC) the implementation of COVID-19 restrictions. To reduce the impacts of ~~the~~ weather conditions and background ~~impacts~~fluctuations, we analyze vehicle~~chose~~ trips with the most similar weather condition as possible and calculated the enhancement metric, which is ~~mean~~ the difference ~~in the CO2 concentration~~ between the on-road CO_2 concentration and the "urban background" CO_2 concentration ~~level~~measured at the tower of the Institute of Atmospheric Physics (IAP), Chinese Academy of Sciences ~~(IAP) tower~~. The results showed that the DC CO_2 enhancement was decreased by 41 (±1.3) parts per million (ppm) and 26 (±6.2) ppm compared to those for the ~~during~~BC and AC trips, respectively~~, after eliminating the fluctuations in CO2 concentrations on polluted days~~. Detailed analysis showed that, during COVID-19 restrictions, there was no difference between weekdays and weekends during working hours (9:00-17:00 local standard time, LST). The enhancements during rush hours (7:00-9:00 and 17:00-20:00 LST) were almost twice those during working hours, indicating that emissions during rush hours were much higher. ~~Compared~~For ~~with~~DC and BC, the ~~reductions in the~~ enhancement~~s~~ reductions during rush hours were much larger than those during working hours. Our findings showed a clear CO_2 concentration decrease during COVID-19 restrictions, which ~~are~~is consistent with the CO_2 ~~concentration and~~emissions reductions due to the pandemic. The enhancement ~~way~~method used in this study is an effective method to reduce the impacts of weather and background fluctuation~~s. and~~L~~o~~ow-cost sensors, which are inexpensive and convenient, could play an important role in further on-road and other urban observations~~should be regularly and more frequently conducted in future work~~.

Introduction:

Since December 2019, the world has been fiercely struggling against a pandemic of a novel ~~c~~Coronavirus named COVID-19, which was ~~firstly~~ first identified in Wuhan, China, (Gross et al., 2020); and then quickly identified ~~by~~ in other countries ~~in~~ of ~~E~~east Asia, and Europe and the United States according to World Health Organization Novel Coronavirus (2019-nCoV) situation reports , (https://www.who.int/emergencies/diseases/novel-coronavirus-2019/situation-reports~~(Le Quere et al., 2020)~~). In Beijing, the first case was confirmed on 20th January 2020, ~~and~~ followed by a quick increase in confirmed cases (~~S~~Figure 1A). From 24th January to 30th April, Beijing enacted a Level-1 response to major public health emergencies (red region ~~-~~ in ~~S~~Figure 1), and lowered the response to Level-2 from 30th April to 6th June, after "zero growth" persisted for almost one month (yellow region, in ~~S~~Figure 1).

As the world faced this highly infectious pandemic without efficient medication, governments ~~carried~~ enacted ~~out~~ similar ~~prohibitions~~ restrictions to prevent the spread of the virus: isolating cases, enacting stay-~~-~~at-~~-~~home orders, forbidding mass gatherings, and closing factories and schools. These ~~prohibitions~~ restrictions highly altered the industrial ~~factory~~ production, energy consumption and transportation volume and led to sharp emission~~s~~ reductions (Liu et al., 2020; Le Quere et al., 2020). As previous inventory studies estimated, by early April 2020, the global daily CO_2 emissions had decreased by 17% (11 to 25% for ±1σ) ~~by early April 2020~~ compared with those in ~~the mean~~ 2019 ~~levels~~, and the ~~absolute~~ total reduction was approximately 1048 (543 to 1~~,~~638) $MtCO_2$ ~~until~~ at the end of April (Le Quere et al., 2020). ~~Among these emissions,~~ ~~e~~Emissions from ground transportation obviously decreased by 36% ~~(28 to 46)~~ (Le Quere et al., 2020). According to Liu *et al.*(~~Liu et al.,~~ *2020*), emissions ~~decreases~~ in China decreased ~~were 6.9~~7% from January to April 2020, ~~in~~ with ~~which~~ ground transportation emissions dropp~~ing~~ed abruptly by 53~~3.4~~% in February and continu~~ing~~ed to decrease by 25.9~~6~~% in March (~~S~~Figure 1B and 1C). In Beijing, during the first quarter ~~in~~ of 2020, passenger traffic volumes decreased 55.6~~6~~%, and ground transport volumes decreased 35.~~2~~% according to the distance-weighted passenger and freight turnover (Han et al., 2020).

~~Although u~~Urban areas are the main CO_2 sources and account for more than 70% of fossil fuel emissions (Rosenzweig et al., 2010), ~~and the~~ CO_2 concentration~~s~~ in urban area~~s~~ ~~is~~ are dominated by weather changes (Woodwell et al., 1973;Grimmond et al., 2002); for example, high wind speed accelerates the mixing and diffusion of CO_2. In addition, the ~~absolute~~ carbon emission reductions (258 MtC, from Le Quere *et al.*(~~Le Quere et al.,~~ 2020)) due to COVID-19 restrictions ~~was~~ were relatively small compared to the CO_2 content in the atmosphere (860 GtC, from Friedlingstein *et al.* (~~Friedlingstein et al.,~~ 2019)) ~~and,~~ carbon uptake by vegetation (the average seasonal amplitude of the net land–atmosphere carbon flux is 41.6 GtC/yr, from Zeng *et al.*(~~Zeng et al.,~~ 2014).~~)~~. Therefore, it is ~~very~~ difficult to detect CO_2 concentration~~a~~ decrease~~s~~ in the urban areas ~~CO_2 concentration decrease~~ directly ~~by~~ from sparse ground observations (Kutsch et al., 2020; Ott et al., 2020). For example, according to the daily CO_2 concentrations in 2019 and 2020 recorded by the tower at the Institute of Atmospheric Physics (IAP), Chinese Academy of Sciences ~~(IAP) tower~~, even though Beijing was within the strictest control/confinement period from 10th to 14th February 2020, stable weather (in which the planetary boundary layer heights (PBLHs) were only ~600 m~~poor diffusion conditions~~) led to CO_2 concentrations that were approximately 90 parts per million (ppm) higher than those on the same date in 2019 (PBLHs were ~ 900 m)(~~S~~Figure 1D). Sussmann and Rettinger (2020) also proved it. ~~Although~~ Despite global emission~~s~~ reduction~~s~~ due to COVID-19 restrictions, they found a historic record high in column-averaged atmospheric carbon dioxide (XCO2) in April 2020 by using Total Carbon Column Observation Network (TCCON) data. ~~By a~~Assuming that the ~~a~~ COVID-19-related CO_2 growth rate reduction of 0.32 ppm/yr^2 in 2020 ~~for~~ at Mauna Loa ~~to be~~ is true and measured (from the UK Met Office; ~~an,~~ overall 8% emission~~s~~ reduction~~s~~ in 2020), they found that there is a ~0.6 year 'delay' to separate~~s~~ TCCON-measured growth rates and the reference forecast (~~without~~ absence of COVID-19 restrictions).

With the knowledge that urban ground transportation was strongly suppressed due to COVID-19 restrictions, we designed on-road observations by using a mobile platform to ~~find~~ detect reduction ~~signals~~s. These observations ~~On-road observations based on mobile platforms, which~~ could provide CO_2 data with higher spatiotemporal resolution ~~CO_2 data~~ than satellite and ground observations, and have been widely ~~conducted~~ used for carbon monitoring in urban and sub-urban ~~regions~~ areas (for instance, on-road CO_2 concentration distributions were presented as transects in urban areas along routes~~transects or communities~~) (Idso et al., 2001;Bush et al., 2015;Sun et al., 2019). Almost ~~However, all~~ all studies ~~explained~~ agreed that weather (for example, wind speed, which is directly associated with ~~the diffusion condition~~CO_2 mixing and dilution) is a dominant factor and should be considered during analysis. Reducing the impact of weather ~~However, it~~ is still a problem~~atic~~ ~~to reduce the impact of weather~~. On the other hand, examining the enhancement, which is the calculated~~s~~ the difference in the CO_2 concentration between urban and rural background observations, could effectively reduce the influence of background CO_2 ~~concentration~~ fluctuations, ~~to analyze CO_2 concentration characteristics in urban areas~~ and this metric has been widely used for monitoring urban carbon emissions and CO_2 concentration~~s~~ (Idso et al., 1998;Idso et al., 2002;George et al., 2007;Mitchell et al., 2018;Perez et al., 2009).

To determine the CO_2 concentration reduction "signal" due to decreased ground transportation emissions ~~decrease~~ during COVID-19 restrictions, we ~~first~~ chose the most similar weather condition~~s~~ as possible; ~~second,~~ and we calculated the enhancements metric by ~~using~~ subtracting the "baseline" IAP tower CO_2 concentration from the observed on-road CO_2 ~~observations~~ concentration ~~minus the "baseline" IAP tower CO_2 concentration~~ to reduce impact of ~~the influence from the~~ background CO_2 fluctuation~~s in the background CO_2 concentration due to weather~~. Our results may provide direct evidence of ground transportation emission reductions due to COVID-19 restrictions, and this method could be an appropriate tool to analy~~s~~ze the CO_2 concentration and emissions related to ~~of~~ urban ground transportation in ~~the~~ future works.
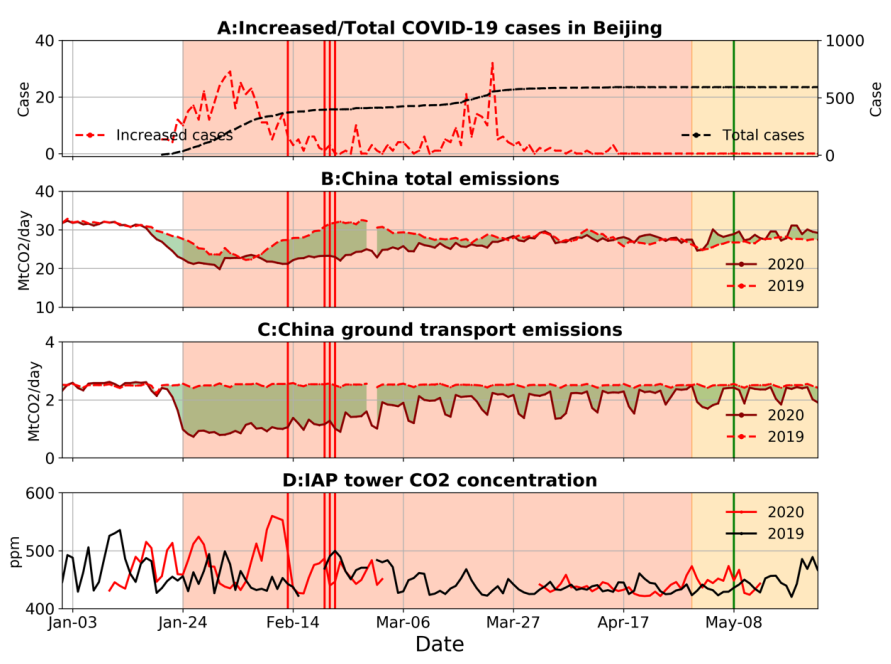
Figure 1. (A) Confirmed increased cases (red) and total cases (black) of COVID-19 in Beijing in 2020; the red/yellow region is the Level-1/2 response periods; vertical lines indicate the on-roads observation dates, red/green lines indicate during and after COVID, respectively. One trip was conducted on 20th February 2019, which was not plotted in Figure 1. (B) China

Methods and Data:

We conducted six on-road observations in Beijing using mobile platforms before (BC; 1 trip: 20th February 2019), during (DC; 4 trips: 13th, 20th, 21st and 22nd February 2020) and after (AC; 1 trip: 9th May 2020) COVID-19 restrictions control (vertical lines in SFigure 1 indicate the trip dates). These trips covered the four ring roads that circled the city:, which are the 2nd (with length of 332.7 km), 3rd (48 km), 4th (64 km) and 5th (99 km) rRing rRoads, from innermost to outermost, as shown in Figure 12. All trips were conducted during the daytime:, in which four of them were on weekdays and two others were on a Saturday. Four trips covered at least one rush hour (7:00-9:00 local standard time (LST) for morning rush hour; 17:00-20:00 LST for evening).

To reduce the influence of the background CO_2 fluctuations, we first chose the similar weather conditions. As shown in Table 1, Three four elements aspects were considered: (1) real-time panoramic reality photographs collected from the IAP tower (photograph available from: http://view.iap.ac.cn:8080/imageview/); (2) the PM$_{2.5}$ (atmospheric particulate matter that has with a diameter of less than 2.5 μm) concentration from the Olympic Sports Center Station (40.003 °N, 116.407 °E, 5 m height, purple square in Figure 12A), which is run by the Ministry of Ecology and Environment of China (Zhang et al., 2015); (3) and wind speed data (available collected from: https://www.wunderground.com/history/daily/cn/beijing/ZBNY/date/2020-5-9) ; and (4) PBLH data, which are related to vertical mixing and diffusion of pollution/CO_2 emitted near the ground (Su et al., 2018). These data were collected from National Centers for Environmental Prediction Global Forecast System (GFS) reanalysis dataset (resolution: 0.25 ° × 0.25 °), which is a globally gridded dataset representing the state of the Earth's atmosphere and incorporating observations and numerical weather prediction model output.

Then, on-road CO_2 concentration enhancements were calculated by subtracting the simultaneous CO_2 concentrations from detected at the IAP tower, which served as implies the "baseline" in for Beijing city (Eq. 1).

$$CO_2 \text{ enhancement} = CO_2 \text{ (on-road)} - CO_2 \text{ (IAP tower)} \qquad \text{(Eq. 1)}$$
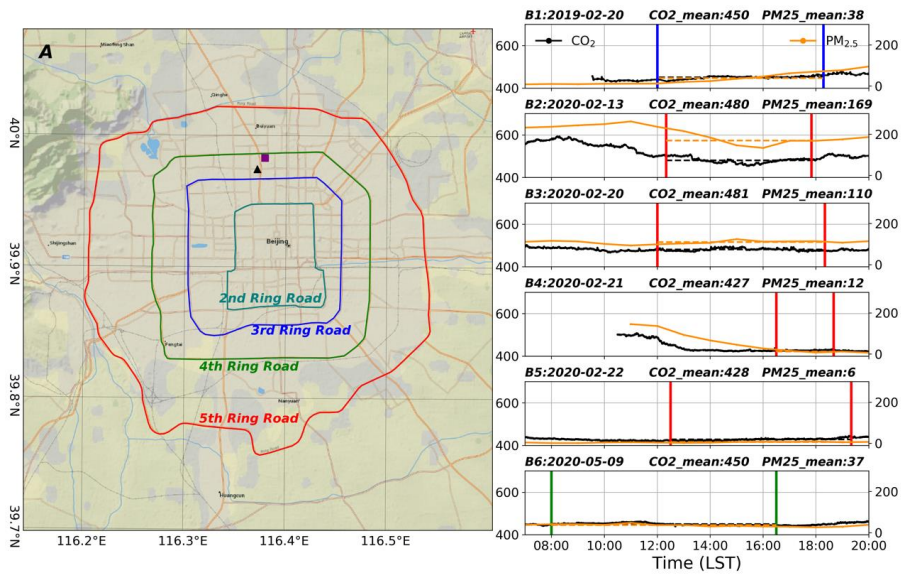
Figure 1~~2~~. A: The locations of the 2nd, 3rd, 4th and 5th rRing rRoads, the IAP tower (black triangle) and Olympic Sports Centre station (purple square); B1-B6: CO_2 concentration ~~from~~ at the IAP tower and $PM_{2.5}$ concentration data from the Olympic Sports Center station during six trips.

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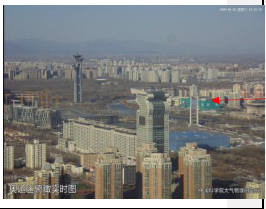*Table 1. Weather conditions during six trips.*

Label/date	Weather condition	Air condition (PM2.5: μg/m³)	Wind speed (m/s)	PBLH (m)	Real-time panoramic photographsReality photos
BC 2019-2-20 (Wed)	Clear day	38	2.5	897.7	
DC 2020-2-13 (Fri)	~~Light~~ Heavily polluted day	169	2.5	589	
DC 2020-2-20 (Fri)	Lightly ~~_~~polluted day	110	1.3	691	

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DC 2020-2-21 (Fri)	Clear day	12	2.5	1587	
DC 2020-2-22 (Fri)	Clear day	6	3.6	1113	
AC 2020-5-9 (Sat)	Clear day	37	1.6	608	

IAP tower CO$_2$ concentration at IAP towerdata:

The IAP tower is a 325 m-high meteorological tower located at 116.3667 °E, 39.9667 °N, 49 m above sea level in northwest Beijing (Figure 12, black triangle) (Cheng et al., 2018). There are three levels ofe CO$_2$ concentration was determined at three levels recordsin this study: surface level (~2 m above the ground), lower level (~80 m) and upper level (~280 m)(Cheng et al., 2018). The CO$_2$ concentrations were measured by a Picarro G2301 greenhouse gas concentration analyszer (Picarro, 2019).The instrument is-was calibrated by using standard gas for every 3 hours, and each calibration lasted 5 minutes by using standard gas. The standard gasses were –from the Meteorological Observation Center of the China Meteorological Administration (MOC/CMA) and, which wereis traced to the World Meteorological Organization (WMO) X2007 scale, and each calibration lasts for 5 minutes. The measurement precision accuracy is-was ~0.1 ppm. All The CO$_2$ concentrations were-was recorded by every 2 seconds, and these data werethen averaged into 1-minute intervals. Before 2020 (including the trip on 20th February 2019), the CO$_2$ concentrations were-was measured at the lower and upper levels alternately for every 5 minutes, and the measurement at each level lasted 5 minutes. After 2020 (including the other 5 trips), the CO$_2$ concentration was continuously measured at the surface level. To maintain consistency as much as possible, we used the lower levellower-level CO$_2$ concentrations before 2020 and the surface levels CO$_2$ after 2020.

On-road CO$_2$ concentration data:

Three different CO$_2$-observationing instruments were carried by vehicles for during six on-road trips (Table 2).

1) On 20th February 2019, a Picarro G2401 (Picarro, 2017) was adopted and installed on a vehicle; the air intake was set on the roof of the vehicle to avoid potential contact with direct plumes emitted from surrounding cars. The intake was linked/connected through a 2 m pipe with a particulate matter filter to the Picarro system (Figure 23A and 23B). The instruments characteristics and precision accuracy have been described by Sun *et al.* (Sun et al., 2019). The CO$_2$ concentrations were collected every 2 seconds and then averaged into 1-minute intervals.

2) During COVID-19 restrictions (surveys on 13th, 20th, 21st and 22nd February 2020), a LI-COR LI-7810 CH$_4$/CO$_2$/H$_2$O trace gas analyszer was adopted, which uses optical feedback-cavity enhanced absorption spectroscopy technology(LI-COR, 2019). This instrument could obtain a CO$_2$ concentration with a precision precision of 3.5 ppm for 1 second and within 1 ppm after 1-minute averaging (laboratory testing). The observation platform of the LI-7810 was

similar to that of the Picarro system. Before departure, the instrument was calibrated by using standard calibration gas (from MOC/CMA) to correct the drift.

3) On 9th May 2020, a low-cost light sensor was adopted and installed on the front windshield of the vehicle (Figure 23C). The instrument mainly consisted of three non-dispersive infrared (NDIR) CO_2 measurement sensors (named K30), and one environment (temperature, humidity and pressure) sensor (named BME). Although the original precision of each K30 is was ±30 ppm, after calibration and environmental correction in the laboratory and before departure, it the accuracy was improved to within ±5 ppm comparing with Picarro (Martin et al., 2017;SenseAir, 2019). Here, we used three K30s in one instrument to recognize and eliminate data anomalies and used the averaged CO_2 concentrations from the three K30s for analysis. Figure 34 shows the details of the experiment conducted on 22nd February 2020, for which installed one low-cost light sensor and Picarro were installed on the same vehicle for on-road monitoring. The results showed that the low-cost light sensor results are were highly consistent with those of the Picarro system, with root mean square errors (RMSEs) less than 5 ppm.

Table 2. Instrument parameters of for six on-road observations

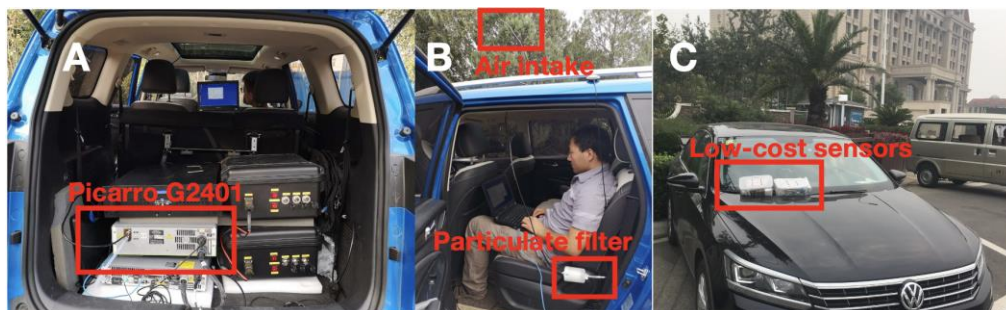| Label	Date	Instrument	PrecisionAccuracy	Temporal resolution (original->processed)
BC	2019-2-20	Picarro G2401	±0.1 ppm	2 seconds -> 1 minute
DC	2020-2-13	LI-COR LI-7810	±3.5 ppm (for 1 second); improved into ±1 ppm (for 1 minute)	1 second -> 1 minute
	2020-2-20	LI-COR LI-7810		
	2020-2-21	LI-COR LI-7810		
	2020-2-22	LI-COR LI-7810		
AC	2020-5-9	Low-cost Sensor (K30)	±5 ppm	2 seconds -> 1 minute

Figure 23. Photographs of the instrument installation for the during on-road observations. (A) and (B) Picarro system installed in the vehicle; (C) low-cost non-dispersive infrared (NDIR) sensors installed on the front windshield of the vehicle.
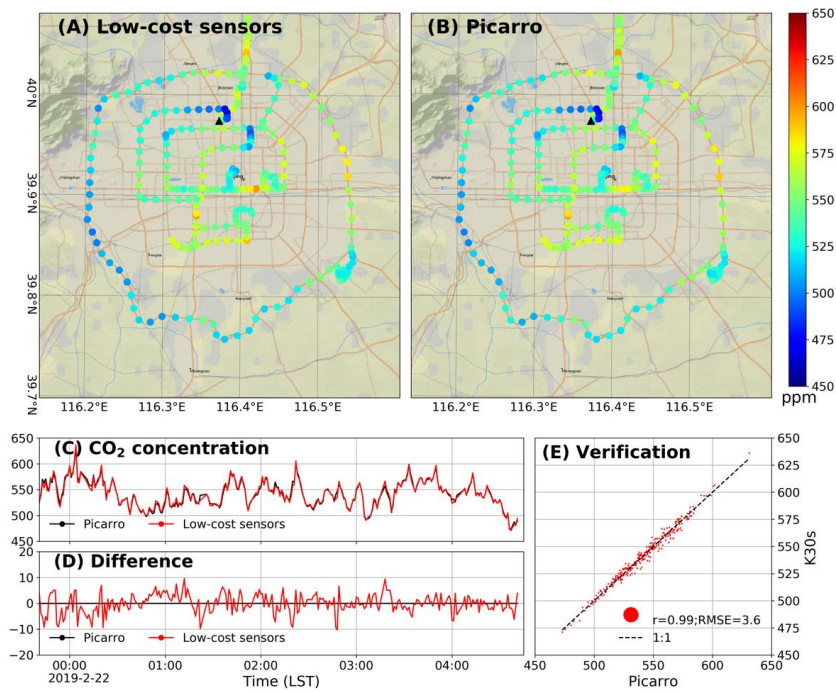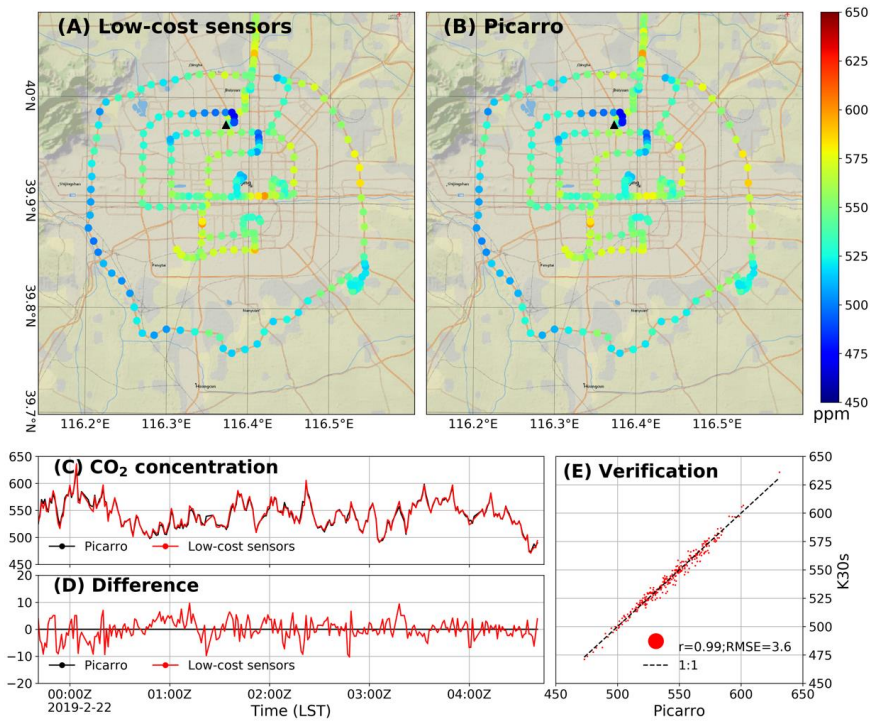
Figure ~~3~~4. Verification of low-cost sensors for on-road observations. (A): Map of CO_2 concentration~~s~~ measured by ~~map of~~ the low-cost sensor; (B): map of the CO_2 concentration ~~of~~measured by the Picarro system on the same vehicle; (C): time series of the CO_2 concentration~~s~~ measured by the ~~using the~~ low-cost sensor and Picarro system; (D): difference (low-cost sensor concentration minus Picarro concentration); (E): scatter plot of the low-cost sensor and Picarro data, with a~~n~~ RMSE of 3.6 ppm.

Auxiliary data and analysis:

The global positioning system (GPS) data ~~during~~for BC and DC were collected by a GPS receiver (BS-70DU) (Sun et al., 2019). ~~During~~For AC, the data were collected by using mobile software (GPS Tracks), which provided time, longitude, latitude, speed and altitude at 1-~~-~~second resolution. These geographic information data were averaged into 1-minute intervals and then matched with the CO_2 concentration data according to time.

Two remote sensing images were adopted (captured on 21st February 2019 at 11:40:00 ~~Local Standard Time (~~LST~~),~~ from a Google Earth image, with 0.37 m spatial resolution; 19th February 2020 at 10:20:08 LST~~,~~ from a Beijing-2 remote sensing satellite~~s~~ panchromatic image, with 0.8 m spatial resolution). Considering the availability of data, we used the images from the closest date and only part of the urban area. The comparison region covered 1~~0~~3.4 km of the 4th-3rd Ring Road (accounting for 2~~0.5~~1 % of the whole road~~, for which the total length is 65.3 km~~) and 1~~3.4~~0 km of the 3rd-4th Ring Road (also ~~accounting for 2~~1~~0.7~~ % of the whole road~~, for which the length is 48.3 km~~). We used a visual interpretation method to obtain the numbers of vehicles on the 3rd and 4th ~~and 3rd~~ Ring Roads for BC and DC~~before and during the COVID-19~~, respectively.

To understand the traffic situation, we also collected the real-time traffic congestion conditions (for each road), road name, geographic information, road type and average speed as one-hour data from the Autonavi Open Platform (https://lbs.amap.com/).

Results:

On-road CO_2 concentration:
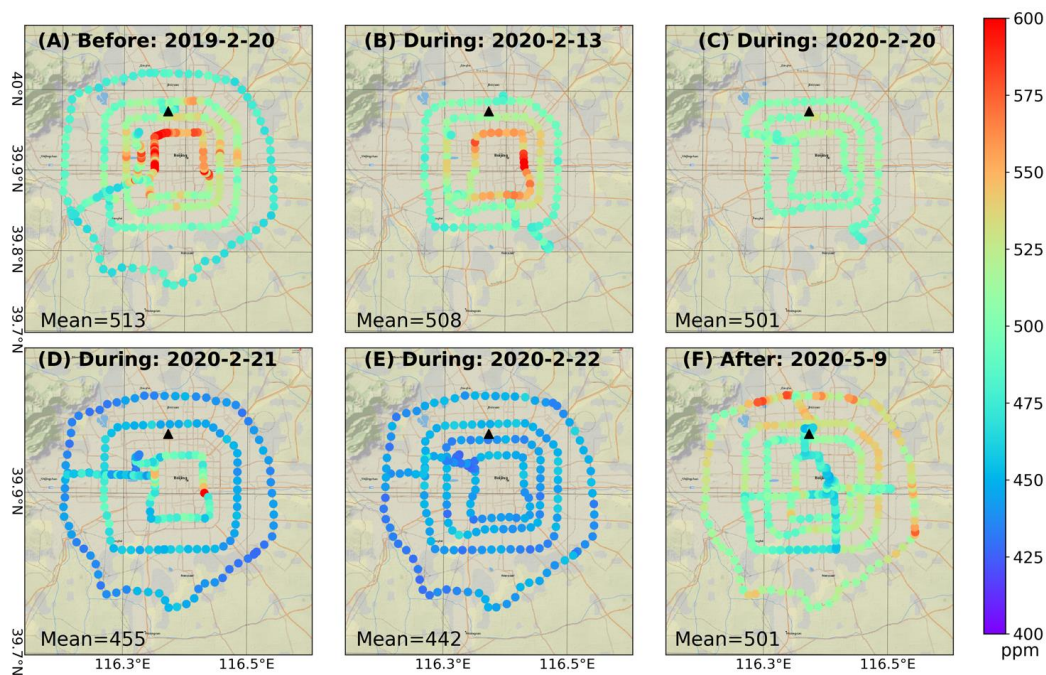
Figure 4~~5~~. CO_2 concentration maps ~~of~~ for six on-road trips. Circle~~s~~ ~~points~~ are the locations of CO_2 concentration records taken at ~~the~~ a 1-minute intervals ~~averaged from data collected every 2 seconds~~ (see methods). All sub-plots have the same colour ~~bar~~scale, ranging from 400 to 600 ppm. The black triangle is the location of the IAP tower. One trip (A:20th February 2019) was conducted before the COVID-19 ~~control~~restrictions, with an average of 513 (with an instrument uncertainty of ±0.1) ppm. Four trips (B-E: 13th, 20th, 21st and 22nd February 2020) were conducted ~~within~~ during the COVID-19 ~~control,~~restrictions, with averages of 508 (±1), 501 (±1), 455 (±1) and 442 (±1) ppm~~and the total average CO_2 was 477,~~ respectively~~ ppm~~. One trip (F: 9th May 2020) was conducted after the COVID-19 ~~control~~restrictions, with an average of 501(±5) ppm.

The CO_2 concentration maps of six on-road trips are shown in Figure 4~~5~~. According to Table 1, we selected four trips as the trips with the most similar weather conditions: one BC trip (20th February 2019, Figure 4A), two DC trips (21st and 22nd February 2020, Figure 4D and 4E) and 1 AC trip (9th May 2020, Figure 4F). Statistically, the average of the 2 DC trips was 444 (±1) ppm, which was 69 (±1.1) and 57 (±6) ppm lower than that of the BC and AC trips, respectively. The other two DC trips (13th and 20th February) were conducted on (lightly/heavily) polluted days, and the CO_2 concentrations on these two days were as high as those during the BC and AC trips.

We chose one DC trip (21st February 2020) for further analysis and compared it to the BC and AC trips. All three trips were conducted on clear days, and their trajectories were similar, from the outermost circle to the innermost circle, and covered one (morning or evening) rush hour. The difference was that the BC and DC trips hit the evening rush hour on the innermost ring road, whereas the AC trip hit the morning rush hour on the outermost ring road. This difference explained why the CO_2 concentration was high on the innermost road (2nd Ring Road) in figure 4A and 4D and on the outermost road (5th Ring Road) in figure 4F. The comparison of the three trips indicated that the CO_2 concentration in Figure 4D was lower than those in Figure 4A and 4F, and the statistics show that the mean CO_2 of the DC trips was approximately 58 (±1.1) and 46 (±6) ppm

lower than those of the BC and AC trips, respectively. In addition, the average CO_2 concentration observed at the IAP tower during the same periods was much lower than the on-road observations (Figure 1B). These concentration differences (gradients) also implied that ground transportation emissions were a major CO_2 source on these urban roads.

However, it was difficult to completely eliminate the impact of background CO_2 fluctuations only though selecting trips with the most similar weather conditions. For example, the PBLHs during two DC trips with the most similar weather were 1587 m and 1113 m, which were almost twice of those during the BC and AC trips (Table 1). The CO_2 concentrations at the IAP tower also indicated that during these two DC trips, the CO_2 concentrations were 427 ($\pm$0.1) and 428 ($\pm$0.1) ppm, which were approximately 20 ppm lower than those for the BC and AC trips (in Figure 1). One trip was chosen as an example for BC (on 20th February 2019), DC (21st February 2020) and AC (9th May 2020) (shown in Figure 5A, 5D and 5F). All three trips were conducted on clear days, and their trajectories were similar that from the outermost circle to the innermost circle and covered one (morning or evening) rush hour. The difference was that the BC and DC trips hit the evening rush hour on the innermost circle road, whereas the AC trip hit the morning rush hour on the outermost circle. This difference explained the CO_2 concentration patterns (Figure 5A, 5D and 5F). The comparison of the three trips indicated that the CO_2 concentration measured in Figure 5D was intuitively lower than that in Figure 5A and 5F, and the statistics show that the DC CO_2 mean was approximately 58 and 46 ppm lower than that of the BC and AC trips, respectively. In addition, the average CO_2 concentration observed by the IAP tower during the same periods was much lower than the on-road observations (Figure 2). These concentration differences (gradients) also implied that ground transportation emissions were a major CO_2 source on urban roads.

The other three DC trips (on 13th, 20th and 22nd February 2020) are shown in Figure 5B, 5C and 5E, with the averaged CO_2 concentrations of 508, 501 and 442 ppm. Due to background CO_2 concentration fluctuations (lightly polluted days), CO_2 concentrations on 13th and 20th February (Figure 5B and C) were as high as those during the BC and AC trips. Statistically, without considering the variation in the background CO_2 concentration, the average of the four DC trips was 477 ppm, which was 36 and 24 ppm lower than that of the BC and AC trips, respectively.
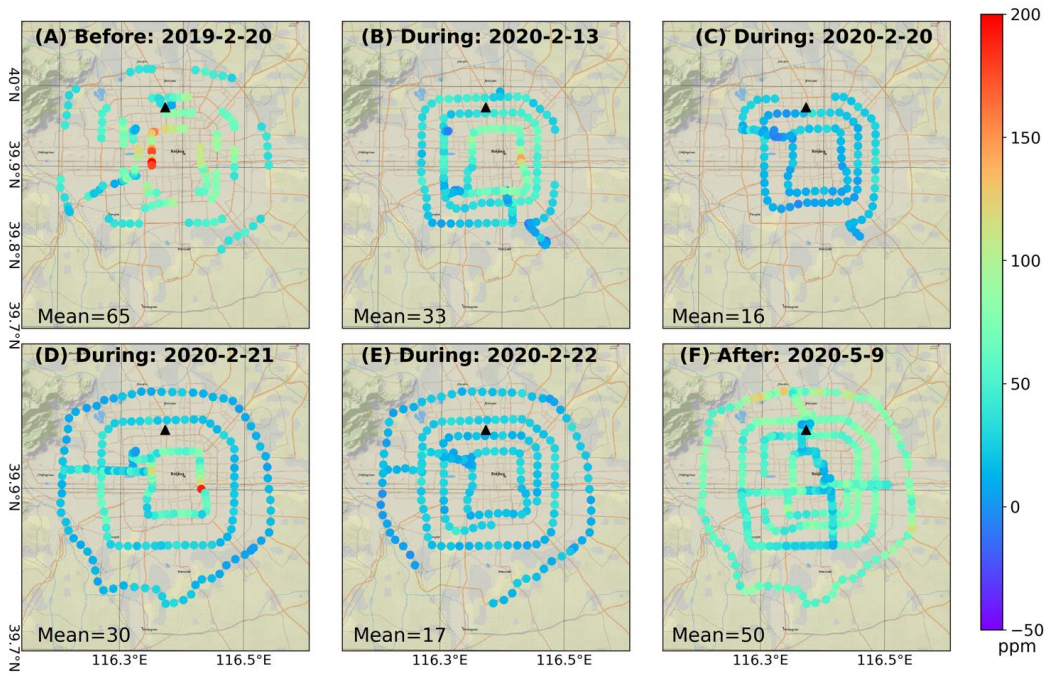
On-road CO_2 enhancement:

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Figure 56. Maps of the CO$_2$ enhancement ~~maps of~~for all six trips ~~using~~ calculated by subtracting the IAP tower measurements from the on-road CO$_2$ measurements ~~minus IAP tower measurements~~ matched ~~by time~~temporally. All sub-plots have the same colour ~~bar~~scale, ranging from -50 to 200 ppm. One trip (A: 20th February 2019) was conducted before the COVID-19 restrictions, ~~control~~ with an average of 65 (±0.2) ppm. Four trips (B-E: 13th, 20th, 21st and 22nd February 2020) were conducted ~~within~~ during the COVID-19 ~~control~~restrictions, with averages of 33 (±1.1), 16 (±1.1), 30 (±1.1) and 17 (±1.1), ~~and the total averaged CO$_2$ enhancement was 24~~ ppm, respectively. One trip (F: 9th May 2020) was conducted after the COVID-19 restrictions, ~~control~~ with an average of 50 (±5.1) ppm.

To further reduce the influence of background CO$_2$ variations, we calculated the CO$_2$ enhancement for six trips by subtracting ~~Figure 6 shows the CO$_2$ enhancement maps of six trips, using~~ the CO$_2$ concentration at IAP tower from the on-road CO$_2$ concentration ~~minus those of IAP tower at the same time~~(shown in Figure 5). The spatial distribution patterns of the enhancement were similar to the distribution of the CO2 concentration maps, in which the enhancements during rush hours were much higher for all trips. Furthermore, the refined spatial distribution of the CO$_2$ gradient implied emissions from ground transportation.

It is worth noting that the enhancements for the four DC trips were almost the same, although the weather conditions (based on the PBHL, PM$_{2.5}$ and wind speed data) during these trips were quite different. However, the DC enhancements were obviously different from the BC and AC enhancements. During the two DC trips on polluted days (13th and 20th February 2020), the mean CO$_2$ concentrations were similar to those during the BC and AC trips (Figure 4B and 4C); however, the enhancements extracted the traffic emission signals from the background, with averages of 33 (±1.1) and 16 (±1.1) ppm (Figure 5B and 5C). Statistically, the average of the four DC enhancements was 24 (±1.1) ppm, which was 41 (±0.2) and 26 (±6.2) ppm lower than those of the BC and AC enhancements.

~~The enhancements present a refined spatial distribution of the CO$_2$ concentration gradient, which implies ground transportation CO$_2$ emissions. As an example, Figures 6A, 6D and 6F presents the BC, DC and AC enhancement maps,~~

respectively. Statistics show that enhancement during the DC trip was 30 ppm, which is 35 and 20 ppm lower than that before and after this trip. The spatial distribution patterns of enhancement were similar to the CO_2 concentration maps, in which enhancements during rush hours were much higher for all trips. Compared to the CO_2 concentration maps, the enhancements showed important information in Figure 6B and 6C. The averaged CO_2 concentrations in these two trips were similar to those during BC and AC (Figure 5B and 5C); however, the enhancements that extracted traffic emission signals from the background, with averages of 33 and 16 ppm (Figure 6B and C), were much lower than those of BC and DC. The enhancement maps also showed more useful information than the CO_2 concentration maps. For example, although the CO_2 concentration throughout the northern half of the 2nd Ring Roads was high (550- 600 ppm) (Figure 5A), the enhancement extracted more specific variations induced by traffic emissions in the northwest (Figure 6A). Generally, the statistical enhancement the average of the four DC trips was 24 ppm, which was 41 and 26 ppm lower than that of the BC and AC trips, respectively. Because of the IAP tower Picarro calibration and measurement procedure (see Method Section), there were regular data gaps for the trip on 20th February 2019 (Figure 6A).

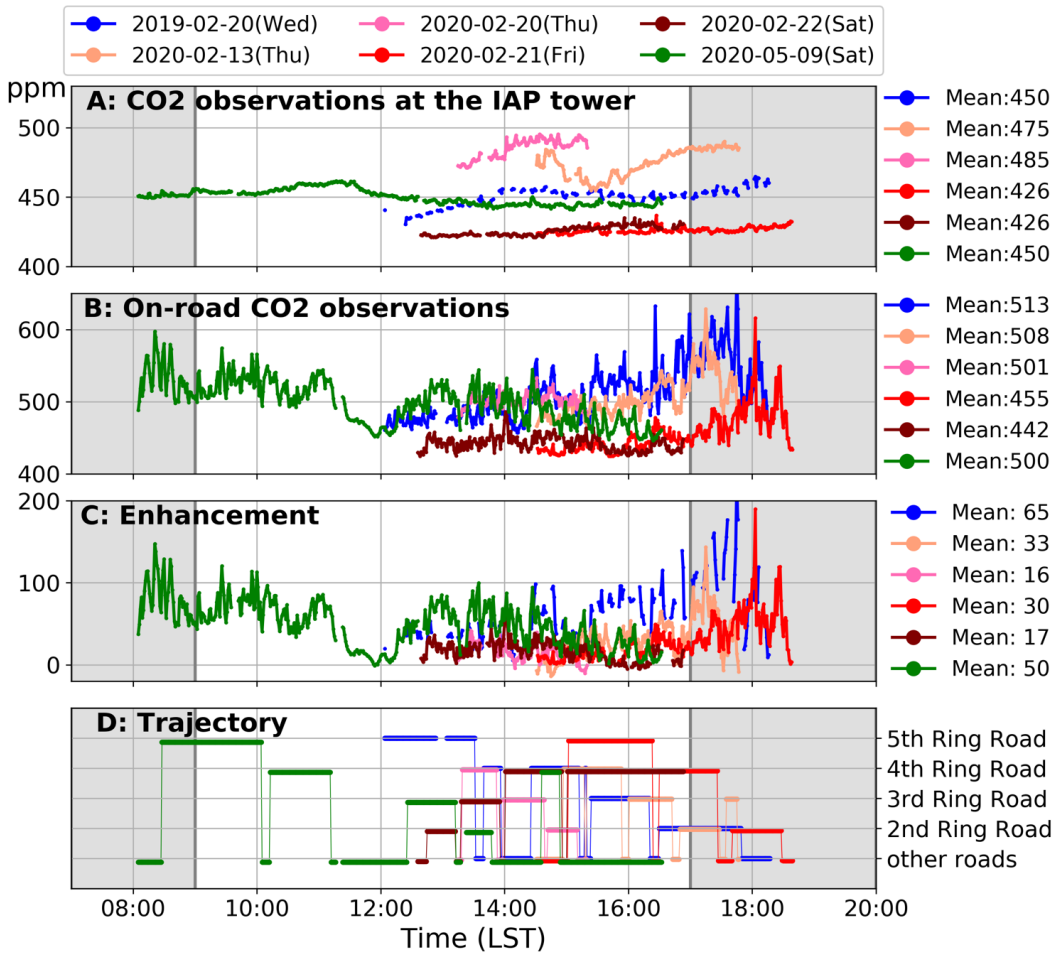**Diurnal variation analysis:**

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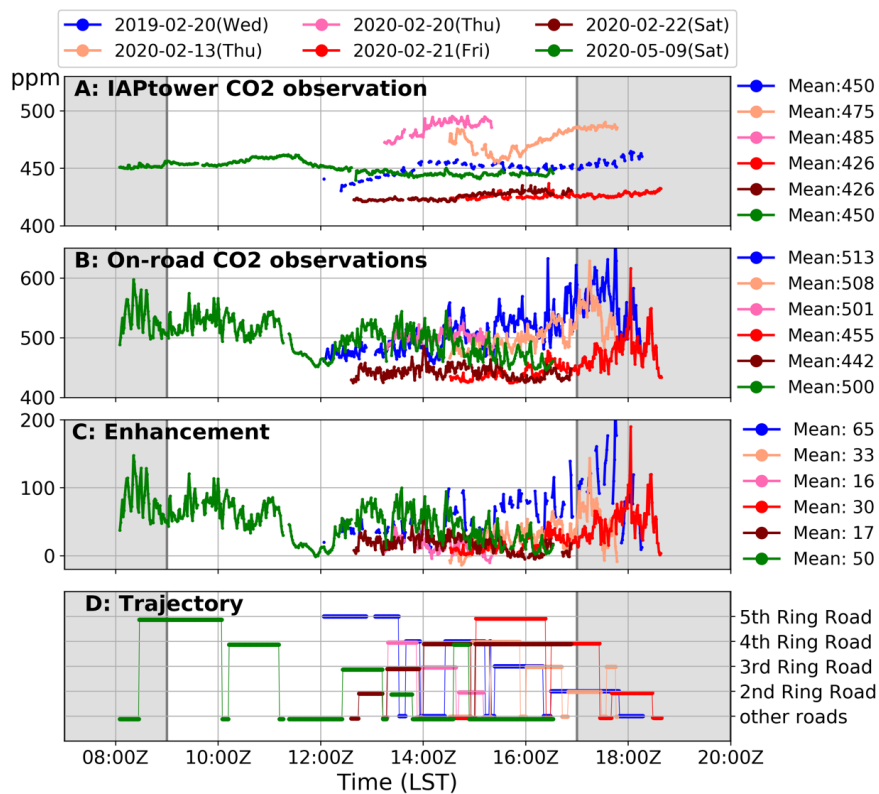
Figure 67. The sSix trips were plotted on a single day. The two grey regions refer to the morning and evening rush hours. The six colourful lines represent the six trips on different days. Four of the 6 trips covered at least one (morning/evening) rush hour. Panel A shows the CO_2 concentration from at the IAP tower during the trips. Panel B shows the on-road CO_2 concentration. Panel C shows the CO_2 enhancements. Panel D shows the six trip trajectories.

Figure 67 shows the diurnal variation from in the CO_2 concentrations from IAP tower observations CO2 concentrations, on-road CO_2 concentrations, enhancements and trajectories for all trips. In Figure 67A, the IAP tower CO2 concentration measured at the IAP tower concentrations were relatively stable, and stable and showed the an difference approximate 50 ppm difference between trips. The CO_2 concentrations at the IAP tower CO2 concentrations during the first two DC trips the two trips during COVID-19 (13th and 20th February 2020) were ~30 ppm higher than those during the BC and AC trips. However, the CO_2 concentrations concentrations during the other two DC trips (21st and 22nd February 2020) were ~20 ppm lower than those during the those during the BC and AC trips trips. These "baseline" CO_2 concentration fluctuations make the on-road observations not directly comparable directly. In Figure 78B, the CO_2 concentrations show a "double-peak" pattern, with peaks during within the morning (7:00-9:00) and evening rush hours (17:00-20:00) rush hours. During the rush hours, the CO_2 concentrations ranged from 500 to 600 ppm, which were approximately 100 ppm higher than the concentrations during working hours (9:00-17:00). The comparison of BC and AC indicates that the CO_2 concentrations measured on 13th and 20th February 2020 did not significantly decrease during 12:00-17:00. However, the CO_2

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concentrations measured on 21st and 22nd February 2020 were much lower (~50 ppm) than those measured during the BC and AC trips. This difference is consistent with the spatial distribution mentioned before and is most likely due to ~~the CO₂ concentration~~ background CO_2 fluctuations.

In Panel C, all DC ~~CO₂~~ enhancements were generally lower than ~~the~~ those ~~of~~ BC and AC enhancements, and the statistics for different time periods are listed in Table 3. However, we ~~still~~ also found ~~very~~ small ~~low~~ enhancements ~~values~~ for BC and AC, similar to thoese for DC~~.~~; ~~F~~for example, ~~the~~ AC enhancement at ~~approximately~~ 12:00 ~~and~~ 16:00 was almost the same as ~~the~~ that of DC enhancement at that time. By examining the ~~With the help of~~ trip routes (Panel D), we found that during that period, the on-road observation vehicle was not driving on the main ring roads. As another example, ~~is the~~ BC enhancement at ~~approximately~~ 18:00~~, which~~ indicates that the enhancement decreased in a stepwise manner, also because the vehicle drove on other roads (Panel D). ~~In Panel C, all DC CO₂ enhancements were generally lower than those of BC and AC, and the statistics for different time periods are also listed in Table 3.~~

Table 3. ~~Statistical analysis of~~ CO_2 enhancement (mean and instrumental uncertainties) for six trips over different periods (ppm)

Label	Observation date ~~Label~~	~~Observation~~ Weather date condition	Total Weather average condition (07:00-20:00)	Morning ~~Total~~ RUSH rush hours hours (07:00-20:00) (07:00-09:00)	Miaiday Morning RUSH hours ~~hours~~ (07:00-09:00) (09:00-17:00)	Evening Working RUSH rush hours hours (09:00-17:00) (17:00-20:00)	Evening RUSH hours (17:00-20:00)
BC	2019-~~BC~~2-20 (Wed)	~~2019-2-20 (Wed)~~ Clear	~~Clear~~ 65 (±0.2)	65 ~~-~~	~~-~~ 54 (±0.2)	54 100 (±0.2)	~~100~~
DC	2020-2-13 (Thu) ~~2020-2-13 (Thu)~~	~~Stable/light area~~ Stable/light pollution	~~Stable/light pollution~~ 33 (±1.1)	33 ~~-~~	~~-~~ 26 (±1.1)	55 ~~26~~(±1.1)	~~55~~
~~DC~~	~~2020-2-20 (Thu)~~	~~Stable//light pollution~~	~~16~~	~~-~~	~~16~~	~~-~~	
	~~2020-2-21 (Fri)~~	~~Windy day~~	~~30~~	~~-~~	~~16~~	~~50~~	
	~~2020-2-22 (Sat)~~	~~Windy day~~	~~17~~	~~-~~	~~17~~	~~-~~	
~~AC~~	~~2020-5-9 (Sat)~~	~~Windy day~~	~~50~~	~~80~~	~~46~~	~~-~~	
	~~Total BC-DC~~		~~41~~	~~-~~	~~35~~	~~48~~	
	~~Total AC-DC~~		~~26~~	~~-~~	~~27~~	~~-~~	

		vy pollution				
	2020-2-20 (Thu)	Stable//light pollution	16 (±1.1)	-	16 (±1.1)	-
	2020-2-21 (Fri)	Windy day	30 (±1.1)	-	16 (±1.1)	50 (±1.1)
	2020-2-22 (Sat)	Windy day	17 (±1.1)	-	17 (±1.1)	-
AC	2020-5-9 (Sat)	Windy day	50 (±5.1)	80 (±5.1)	46 (±5.1)	-
	Total BC-DC		41 (±1.3)	-	35 (±1.3)	48 (±1.3)
	Total AC-DC		26 (±6.2)	-	27 (±6.2)	-

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The average of CO₂ mean enhancement for the whole BC trip was 65 (±0.2) ppm, and the average for the the evening rush hours (100 ±0.2 ppm) was two times that of for the working hours (54 ±0.2 ppm). This result implies that the increase in vehicle volume in during the evening rush hours leads to large traffic emissions and an increase in the on-road CO_2 concentration. For DC, all trips covered the working hours, with a low enhancement of approximately 20 ppm. There was not obvious difference between weekdays and weekends during this periodworking hours, which indicated that there was no "week effect". The reason may be that because the government encouraged people to work remotely at home. Therefore, even on weekdays, according to traffic conditions, the commute volume was low was small(SFigure 2). Among these four trips, two (on 13th and 20th February 2020) covered the evening rush hours with high averaged enhancements of 55 (±1.1) and 50 (±1.1) ppm. Therefore, the total average enhancements averages forof these two trips were higher than those for of the other two trips, which covered only only working hours. For AC, on 9th May 2020, although it was a Saturday, many residents chose to go out of town for the weekends. The morning rush hours still existed, with a high enhancement of 80 (±5.1) ppm, and then during the working hours, the enhancement decreased to 46 (±5.1) ppm.

The comparison of trips showed that the averaged CO₂ enhancement for the from 4 whole DC trips was 41 (±1.3) and 26 (±6.2) ppm lower than that from for the BC and AC trips, respectively. Compared to tThe BC trip, the averaged AC enhancement was 15 15 (±5.3) ppm lower than the average BC enhancement. This difference may be caused by two factors: 1) The first relates to "weekly effects":; as previously mentioned; a previous study also suggested that, compared to that during weekdays, the average daily traffic CO₂ emissions during weekends in the north part of the fifth Ring Road (LinCui Road - Anli Road, 3 km) decreased by 5% throughout wholein 2014 according to the Motor Vehicle Emission Simulator model (from 131.74 t/d to 126.33 t/d)(Zheng et al., 2020).; 2) until Until 9th May 2020, although there were approximately 30 days without increased increases in COVID-19 cases in Beijing, the city was still under Level-2 response control; social life was recovering, but had not yet completely recovered.

Analysis of CO₂ enhancement on for independent time periods and roads:
According to the previous analysis, we found that enhancement exhibited a strong correlation with the time (rush or working hours) and road types. Therefore, we statistically analyszed the CO₂ enhancements according to the road types and time periods, as shown in Figure 78. In Figure 78A, on 13th and 20th February 2020, the CO₂ concentrations on the other, 2nd, and 4th rRing rRoads and all roads were at the same levels as those during the BC and AC trips. However, in Figure 78B, the the enhancement showed that the four DC enhancementsfour trips during COVID-19 were generally lower than those during AC and BC for all road types. Although on the 2nd Ring Road, the DC trips enhancements on 13th and 21st February 2020 were

almost the same as the BC and AC ~~trips~~enhancements, the DC trips were during rush hours, whereas the AC and BC trips were during working hours. Some very high deviations also occurred (rush hours on the other roads~~,~~ 2nd and 5th ~~r~~Ring ~~r~~Roads), which indicates the dispersion of the CO_2 enhancement. The reason for this difference is that we classified all roads excluding the ring roads as other roads, which may have included arterial and residential roads, so the different road types may have increased the deviation. For the 2nd and 5th ~~Ring~~ ring roads, high deviation occurred because during rush hour, traffic flow and transportation var~~ied~~y greatly and result~~ed~~ in drastic changes ~~to~~ in the CO_2 enhancement, which also cause~~ds~~ much higher deviations. ~~We also calculated specific statistics, which are listed in Table 4.~~ After a statistical significance test, we found that the CO_2 enhancement difference between working times and rush hours for all trips was significant ($p < 0.02$, assuming that α=0.05). The CO_2 enhancement for BC was also significantly different from that for DC ($p < 0.05$); however, the difference between the AC and BC enhancements was not significant. This suggests that the decreased CO_2 enhancement observed during the COVID-19 restrictions was significantly different from those before and after the COVID-19 restrictions. We also calculated specific statistics, which are listed in Table 4.
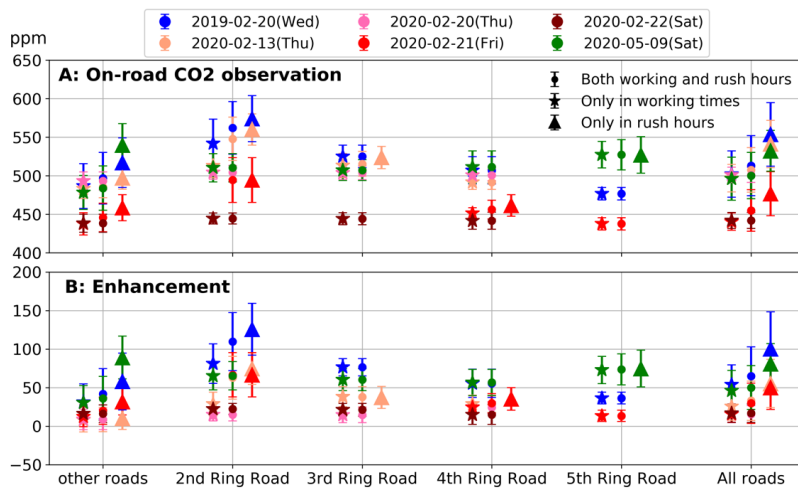
Figure 7~~8~~. Statistical~~ly~~ analysis (mean and one standard deviation) of all on-road trips according to the road types and times. Panel A shows the on-road CO_2 concentration. Panel B shows the CO_2 enhancement.

Table 4. Statistical analysis (mean/one standard deviation) of the CO_2 enhancement for six trips according to the time~~s~~ and road type~~s~~

Label	~~date~~Date	Time	~~other~~ Other roads	2nd Ring Road	3rd Ring Road	4th Ring Road	5th Ring Road	All roads	Significance test (p)	
									Working hours compared to rush hours	DC/AC compared to BC
BC	2019-2-20 (Wed)	Working hours	31/24	81/26	77/11	56/18	37/8	54/26	0.015	-
		Rush hours	58/37	125/34	-	-	-	100/48		-
		Both	42/33	109/38	77/11	56/18	37/8	65/38	-	-
DC	2020-2-13 (Thu)	Working hours	8/16	29/15	38/13	29/11	-	26/18	0.018	-

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		Rush hours	10/±14	74/±20	37/±14	-	-	55/±31		-
		Both	9/±16	63/±28	38/±13	29/±11	-	33/±26	-	0.041
	2020-2-20 (Thu)	Working hours	9/±13	15/±8	14/±10	24/±8	-	16/±11	-	-
		Rush hours	-	-	-	-	-	-		-
		Both	9/±13	15/±8	14/±10	24/±8	-	16/±11	-	0.001
	2020-2-21 (Fri)	Working hours	12/±13	-	-	25±7	13±7	16±10	0.002	-
		Rush hours	32/±17	67/±29	-	35/±15	-	50/±28		-
		Both	20/±18	67/±29	-	30/±13	13/±7	30/±26	-	0.026
	2020-2-22 (Sat)	Working hours	16/±11	22/±7	21/±8	15/±13	-	17/±12	-	-
		Rush hours	-	-	-	-	-	-		-
		Both	16/±11	22/±7	21/±8	15/±13	-	17±12	-	0.001
AC	2020-5-9 (Sat)	Working hours	30/±22	65/±18	60/±14	57/±17	73/±18	46/±26	0.008	-
		Rush hours	89/±28	-	-	-	75/±24	81/±26		-
		Both	36/±29	65/±18	60/±14	57/±17	73/±20	50/±28	-	0.41

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Discussion:

Analysis of the c~~C~~orrelation ~~analysis~~ with traffic flow：

It was difficult to obtain a quantitative evaluation of the influence of COVID-19 restrictions on CO_2 emissions from traffice ~~during our study period~~ because ~~there were~~ of limited data. In this study, we found that the one--trip enhancement ~~during~~ for DC (on 21st February 2020, with ~~the most similar~~ weather conditions and a ~~and~~ route that were the most similar to those for the BC and AC trips) ~~as trips during BC and AC)~~ was 30 (±1.1) ~~-~~ppm. The enhancement accounted for 46% of that ~~during~~ for BC (65 ±0.2 ~~-~~ppm), and the enhancement ~~during~~ for AC (50 ±5.1 ppm) account~~ed for~~ 77% of that for ~~during~~ BC. Here, we adopted four data~~sets~~ and methods to explain our hypothesis that the decrease in traffic volume led to a reduction in on-road CO_2 emissions and concentration during the COVID-19 ~~control~~restrictions. First, according to the "analysis of road traffic operation in Beijing during COVID-19 in 2020" published by the Beijing Transport Institute, during the first 8 weeks (from 1st February to 31st March, the DC period in this study), the Beijing ground transportation index (calculated based on the ratio of ~~congestion~~ congested road length to the ~~and~~ whole road length) decreased by 53% compared to that ~~on to~~ normal days, ~~;~~ whereas, during 1st April to 31st May, the index recovered to 92% (Zhang, 2020). The index implied that traffic flow ~~of~~ for DC ~~is~~ was dramatically decreased compared to that ~~of~~ for BC, and the index for AC almost recovered ~~almost~~ but not completely. This index variation is consistent with our observations ~~results~~. Second, two remote sensing images from similar dates were adopted (Figure 8~~9~~). According to statistics and estimations based on coverage area, we found that the BC traffic flows on the main roads of the 4th and 3rd Ring Roads ~~are~~ were 227 and 226 veh/km (vehicles per kilomet~~e~~re), respectively. However, the DC traffic flow decreased to 35 and 34 veh/km, ~~with~~ reflecting a reduction of approximately 85%. ~~Simply~~ With the assuming that emission factors were the same, the CO_2 emissions on roads ~~during~~ for DC may have sharply

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420 decreased by approximately 85% compared to those ~~during~~ for BC. This difference is higher than the passenger transportation decrease estimated by Han *et al.*'s ~~(Han et al.,~~ 2020) (5~~6~~5.6% in the first quarter of 2020) because ~~the~~ remote sensing image~~s~~ ~~is~~ are ~~a~~ snapshot~~s~~ and cover only part of the urban area. Moreover, ~~, and~~ Hans' results are the average of the first three months and the entire Beijing administrative region. Third, we also used ~~collected real-time~~ traffic congestion

condition~~s~~ data, although with low temporal and spatial resolution, to indicate the on-road traffic flow and emissions (Figure

425 9)~~(for each road), road name, geographic information, road type and average speed for one-hour data from the Autonavi Open Platform (https://lbs.amap.com/). The data, although with low temporal and spatial resolution, could be used to show traffic conditions on roads, and then indicate the on-road traffic flow and emissions (Figure 10).~~ Fourth, the vehicle speed

maps of the six trips were ~~also~~ plotted (Figure 1~~0~~1). Overall, these maps reflect the spatial patterns of road traffic conditions

during the surveys and could also reflect the specifics on a single road. However, these maps are ~~subject~~ sensitive to

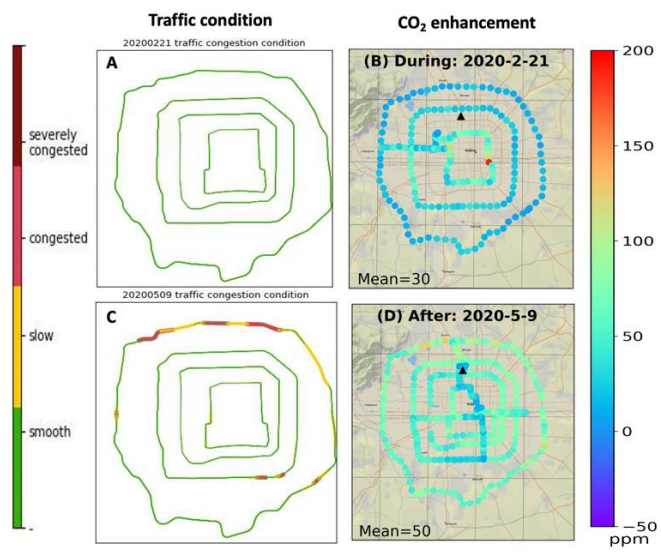430 subjective speed variations caused by drivers, such as when facing traffic lights.

Figure 8~~9~~. Traffic volume comparison ~~by~~ with

using remote sensing images. (A) Coverage region of remote sensing images (purple polygon) and example region shown on

435 *the right (red square); (B) remote sensing images from Google Earth on 21st February 2019 at 11:42:00 (LST), with a*

spatial resolution of 0.37 m for multispectral band images; 61 vehicles on the main road were interpreted (labelled by blue

polygons); (C) remote sensing image from the Beijing-2 satellite on 19th February 2020 at 10:20:08 (LST), with a spatial
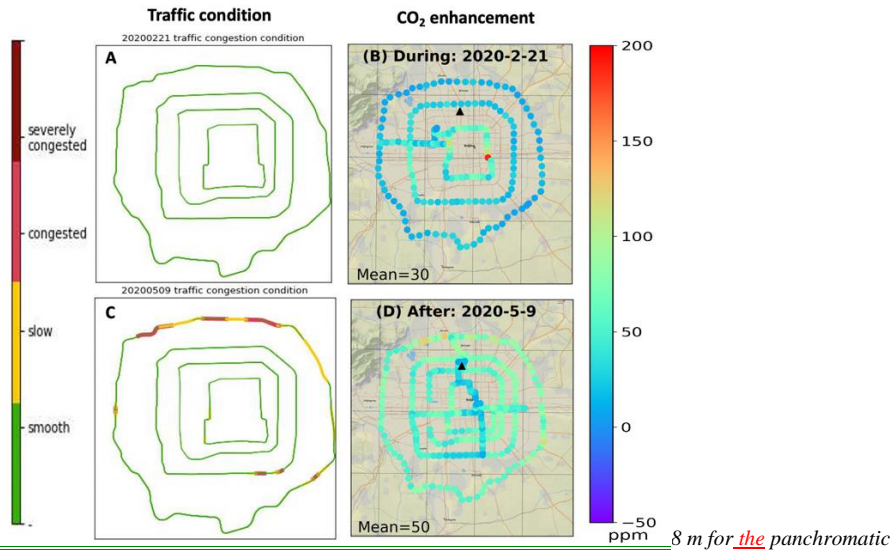
resolution of 0._____8 m for _the_ panchromatic band images and 24 vehicles labelled ~~by~~ _with_ red polygons.
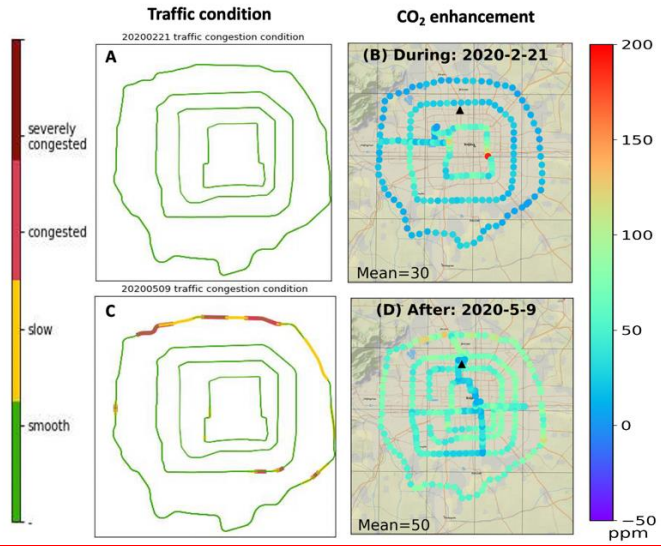
Figure 910. Comparison of tTraffic conditions comparison with the CO_2 enhancement. (A) Traffic conditions on 21st February 2020; (B) CO_2 enhancement on 21st February 2020; (C) traffic conditions on 9th May 2020; (D) CO_2 enhancement on 9th May 2020.
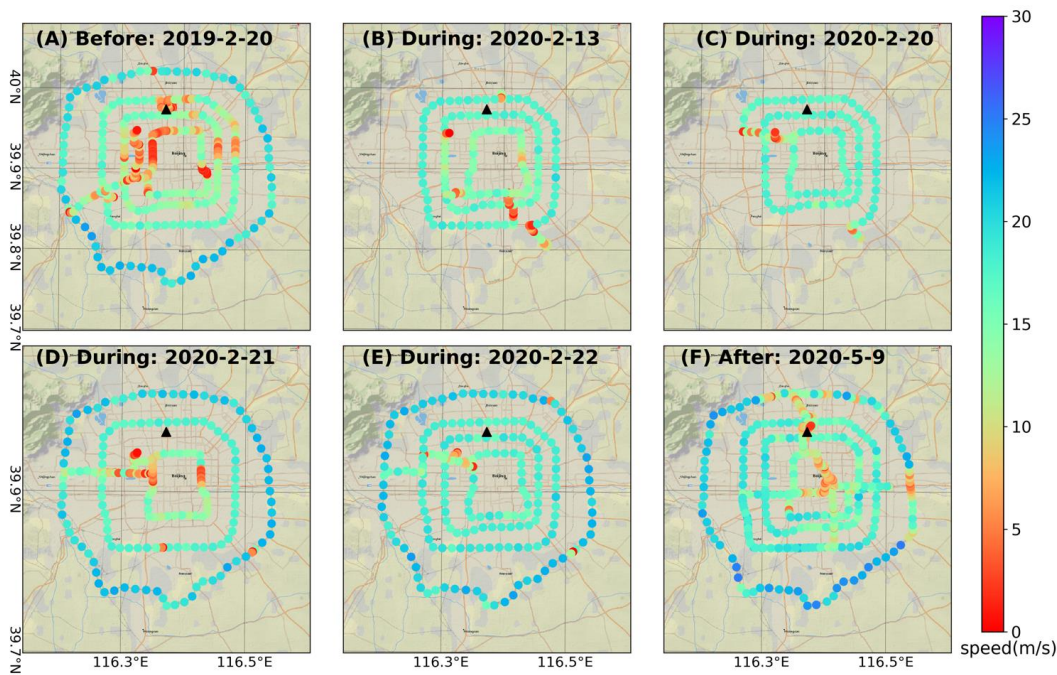
Figure 10~~1~~. Speed maps of six trips, ranging from 0 to 30 m/s. One trip (A: 20th February 2019) was conducted before the COVID-19 ~~control~~restrictions. Four trips (B-E: 13th, 20th, 21st and 22nd February 2020) were conducted during the COVID-19 restrictions~~control~~; one trip (F: 9th May 2020) was conducted after the COVID-19 restrictions~~control~~.

Uncertainty analysis:

In this research, ~~The~~ uncertainty ~~of this research~~ mainly existed in the following terms:

(1) Uncertainty from the observation instruments.

In this study, four instruments were adopted for measuring CO_2 concentrations: three for on-road observations (a Picarro G2401, with an accuracy of approximately 0.1 ppm; a LI-COR LI-7810, ~1 ppm; and a low-cost sensor, no more than 5 ppm) and one for the IAP tower observation (Picarro G2301, ~ 0.1 ppm). During analysis, both the proposed enhancement method and the CO_2 concentration/enhancements of different trips were compared using linear analysis (addition/subtraction). Therefore, the enhancement uncertainties from the observation instruments were: ~0.2 ppm for BC, ~1.1 ppm for DC, less than 5.1 ppm for AC, ~1.3 ppm for comparing BC and DC, and less than 6.2 ppm for comparing DC and AC. Note that the standard deviations shown in Table 4 mainly presented CO_2 concentration fluctuations within specific periods and on certain roads and uncertainty from instruments (relatively small).

~~(1)~~(2)   The IAP tower CO_2 concentration was used as the background ~~in~~from Beijing.

In this study, the IAP tower data were adopted as the urban background CO_2 concentration in Beijing. Its measurement footprint was influenced by two factors: wind speed/direction and air intake height. For wind speed/direction, in Beijing, the main wind directions were northwest (winter) and southeast (summer) (Cheng et al., 2018). ~~However, IAP tower data were collected from different levels, as described in the method section.~~ Generally, high-level data ~~would~~ have a large footprint and good representativeness ~~and cover large regions~~. For example, Cheng *et al.* (~~Cheng et al.,~~ 2018) showed that CO_2 data recorded at 280 m height ~~level CO_2 data~~ have an average~~d~~ fetch of ~17 km, which ~~may~~ covers a major part of the city; data collected at 80 m height ~~level data~~ have an average~~d~~ fetch of ~8 km; data collected at ~~and~~ 8 m height ~~level data~~ may have

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ana averaged fetch of only ~230 m;. and the fetch at the surface level (2 m) may be smaller. Therefore, there are two uncertainties. The first is the height variation during the observation trips. Due to the data availability and for comparison consistency, we chose the lower- and surface-level data. According to Cheng *et al.* (2018), the CO_2 concentration at the 80 m height is ~15 ppm higher than that at the 8 m height. Therefore, if this difference between the lower level and surface level was added, the BC enhancement would increase (~15 ppm), which means that the DC enhancement would be even lower (~56 ppm) than the BC enhancement. The other is the difference between the surface level data and 280-metre height data in different seasons. Due to the data availability and comparison consistency, we chose the lower and surface level data. According to Cheng et al.(Cheng et al., 2018), the CO2 concentration at the 80 m height level is ~15 ppm higher than that at 8 m. Therefore, adding this difference between the lower level and surface level, the BC enhancement would increase (~15 ppm), which means that the DC enhancement would be even lower (~56 ppm) than the BC enhancement. According to Cheng *et al.* (2018), the monthly averaged CO_2 showed a relatively stable difference among the different heights: the CO_2 at the lower level was approximately 40 ppm higher than that at 280-metrs in February and approximately 30 ppm higher in May. The AC enhancement should increase 10 ppm additionally, which means that the DC enhancement would be even lower (~36 ppm) than the AC enhancement. Considering these uncertainties, the This results support is consistent with our hypothesis.

(3) Influences of vegetation sinks and natural changes.

To understand the CO_2 variability impacted by natural sinks (especially for vegetation), we used the dynamic vegetation and terrestrial carbon cycle model VEGAS (Zeng *et al.*, 2014) to simulate the terrestrial biosphere-atmosphere flux (Fta) in Beijing during 2000-2020 (SFigure 3). The model was run at a 2.5×2.5-degree resolution from 1901 to June 2020, forced by observed climate variables, including monthly precipitation and hourly temperature. Although precipitation and temperature in 2020 were higher than the climatology (average of last 20 years), the difference between the Fta in 2020 and the average was within one standard deviation. This suggests that the Fta in 2020 was not obviously unusual compared to that over the last 20 years. We also analysed the CO_2 concentration at the Shangdianzi station in the Beijing rural region, which is one of the three WMO/GAW regional stations in China, to determine the CO_2 background variation (Fang et al., 2016). The results (SFigure 4) showed that the background CO_2 concentration variation mainly induced by natural factors from February to May was only approximately 5 ppm. However, these two factors (vegetation flux and natural changes) both indicate areas far larger than Beijing urban areas. Because the location of the IAP tower and the tracks of the on-road observations are both in urban Beijing and we used the enhancement method, these factors were reduced.

(42) When data were collected, especially when switching between lower and upper levels, a large amount of data was lost. However, because the data gaps were evenly distributed and the IAP tower CO_2 concentrations were relatively stable, we assumed that it would not affect the final statistical results.

(53) In this study, our on-road observations did not have a fixed route or beginning/ending time, which means that the observations on different dates represented different roads. Therefore, we analyzed analysed a wide time range of observations (rush hours, working hours or whole days), which may have also caused uncertainty.

Conclusion

The CO_2 emission reduction caused by COVID-19 restrictions is an opportunity to test our ability to collect CO_2 observations in urban regionsareas. In this study, we chose on-road CO_2 concentrations as the target, because ground transportation is the main source of CO_2 in urban areas and was remarkably influenced by policy restrictions due to the COVID-19 pandemic. We conducted six on-road observations in Beijing, including one trip before COVID-19 restrictions, in February 2019; four trips during COVID-19 restrictions, in February 2020; and one trip in May 2020, after COVID-19 restrictions had been eased. aiming at traffic emissions, which the potentially represents the largest reduction source in urban areas due to COVID-19, we conducted six on-road observations in Beijing, China. The results showed that on-road CO_2 concentrations were strongly affected by traffic emissions and weather. However, the enhancement metric, which was the

difference ~~of~~ in the on-road CO_2 concentration and the city "background", reduced the impact of background CO_2 fluctuations. The results showed that ~~during~~ for DC~~COVID-19~~, the total average CO_2 enhancements of the four trips were 41 (±1.3) ppm and 26 (±6.2) ppm lower than those ~~before and after~~for BC and AC, respectively. Detailed analysis showed that this reduction commonly existed on all road types during the same time period (rush hours/working hours). For the DC trips, ~~During COVID-19,~~ there was no significant difference during work hours between weekdays and weekends. T~~During rush hours, t~~he enhancements during rush hours were much higher than those during working hours, and compared with the enhancement reduction during rush hours for BC, that for ~~the~~ DC ~~enhancements reduction during rush hours~~ was mo~~st~~re obvious. Our findings, which show a clear decrease ~~during~~ for DC compared with ~~those during~~ BC and AC, are consistent with the COVID-19 restrictions~~control~~, which may be direct evidence of reductions in CO_2 concentrations and carbon emissions. On-road CO_2 observations are an effective way to understand and analy~~z~~se the urban carbon CO_2 concentration distribution and variation and should be regularly and more frequently conducted in future work. ~~With t~~The development and successful application of the miniaturized and low-cost CO_2 monitoring instruments used in this study (Khan et al., 2012;Shusterman et al., 2016;Martin et al., 2017;Mueller et al., 2020;Bao et al., 2020)~~, these instruments~~ will greatly aid in the ~~help~~ collect~~ion of~~ on-road observations and even high-density network observations and play a key role in future urban carbon observations.

Author contributions

Pengfei Han, Bo Yao and Ning Zeng conceived and designed the study. Di Liu summarized the results and wrote the draft of the paper. Wanqi Sun and Pengfei Han designed and conducted the on-road observations. Pucai Wang provided the IAP tower observation data. Ke Zheng, Zhiqiang Liu, Han Mei and Qixiang Cai helped to collect, process and ~~analyze~~ analyse data.

Competing interests.

The authors declare that they have no conflicts of interest.

Acknowledgements：

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