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Dramatic decline of observed atmospheric CO₂ and CH₄ during the COVID-19 lockdown over the Yangtze River Delta of China

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Abstract

The temporal variation of greenhouse gas concentrations in China during the COVID-19 lockdown in China is analyzed in this work using high resolution measurements of near surface ΔCO₂, ΔCH₄ and ΔCO concentrations above the background conditions at Lin’an station (LAN), a regional background station in the Yangtze River Delta region. During the pre-lockdown observational period (IOP-1), both ΔCO₂ and ΔCH₄ exhibited a significant increasing trend relative to the 2011-2019 climatological mean. The reduction of ΔCO₂, ΔCH₄ and ΔCO during the lockdown observational period (IOP-2) (which also coincided with the Chinese New Year Holiday) reached up to 15.0 ppm, 14.2 ppb and 146.8 ppb, respectively, and a reduction of ΔCO₂/ΔCO probably due to a dramatic reduction from industrial emissions. ΔCO₂, ΔCH₄ and ΔCO were observed to keep declining during the post-lockdown easing phase (IOP-3), which is the synthetic result of lower than normal CO₂ emissions from rural regions around LAN coupled with strong uptake of the terrestrial ecosystem. Interestingly, the trend reversed to gradual increase for all species during the later easing phase (IOP-4), with ΔCO₂/ΔCO constantly increasing from IOP-2 to IOP-3 and finally IOP-4, consistent with recovery in industrial emissions associated with the staged resumption of economic activity. On average, ΔCO₂ declined sharply throughout the days during IOP-2 but increased gradually throughout the days during IOP-4. The findings showcase the significant role of emission reduction in accounting for the dramatic changes in measured atmospheric ΔCO₂ and ΔCH₄ associated with the COVID-19 lockdown and recovery.

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Introduction

The concentration of CO₂ in the atmosphere has increased from approximately 277 ppm in 1750 (Joos and Spahni, 2008) at the beginning of the industrial era, to 410.5 ppm in 2019 (WMO, 2020). The increase in anthropogenic emission of greenhouse gases (GHGs), in combination with other anthropogenic drivers such as reduction of CO₂ uptake by the biosphere, are extremely likely to be the dominant cause of the global climate change since the mid-20th century (IPCC, 2014). It was reported that the CO₂ emissions in China reached up to 11,255.88 million tons in 2018, accounting for roughly 30% of the total global emissions of CO₂ (Crippa et al., 2020), in spite of the great efforts made by Chinese government to reduce emissions in China (Guan et al., 2009).

Unprecentedly, the outbreak of the 2019 Coronavirus epidemic (COVID-19) led to strict lockdown measures implemented economy-wide for the first time on January 23, 2020 in China (Wu et al., 2020). Such lockdown policies caused significant reduction in global fossil fuel consumption (Le Quéré et al., 2020; Liu et al., 2020), which provides a unique opportunity to unravel the potential impact of reduced fossil fuel emissions on the concentrations of air pollutant and greenhouse gases (Le Quéré et al., 2020; Liu et al., 2020; Myllyvirta et al., 2020; Zheng et al., 2018). Wide-spread improvement in air quality has been widely reported following lockdown in the world’s most polluted cities (Shrestha et al., 2020). Nevertheless, sporadic air pollution episodes frequently occurred in eastern China during COVID-19 (Chang et al., 2020; Su et al., 2020; Wang et al., 2020), which were attributed to a wide range of causes, including much shallower boundary layer (Su et al., 2020), regional transboundary transport (Huang et al., 2020), the enhanced conversion of NOx to particulate nitrate (Chang et al., 2020), aerosol heterogeneous chemistry promoted by high humidity (Le et al., 2020), and enhanced biomass burning (Wang et al., 2021).

Even with these known changes, previous research focusing on the changes in near-surface CO₂ and other long-lived GHGs concentrations remains limited. On a global scale, a reduction of 0.08–0.23 ppm in annual CO₂ concentration was estimated by the Global Carbon Project (GCP), due largely to the impact of COVID-19 lockdown (WMO, 2020). The similar conclusion was reached by Carbon Brief (Betts et al., 2020). In the Northern Hemisphere, a 0.25 ppm decrease of CO₂ was expected at the end of April (Zeng et al., 2020). One finding has demonstrated that the reduction of CO₂ was mainly limited to local sources (Chevallier et al., 2020). However, no significant changes in CO₂ were observed in other places, such as near Gartow in Germany, within the time period constrained by their own local COVID-19 lockdown (Kutsch et al., 2020). As such, it is imperative to see whether there is a reduction of CO₂ from synergistic analysis on more geographic scales, or if this is merely a localized phenomenon.

The purpose of this present study is to unravel the potential impact of COVID-related shutdown measures on atmospheric CO₂ concentrations at a remote site, in specific Lin’an station (LAN, 119.72°E, 30.3°N, 138.6 m a.s.l.), which is a regional background station located at the western edge of the Yangtze River Delta (YRD) conurbation in Eastern China.

1. Data and methods

The present study is based on continuous measurements of atmospheric CO₂, CH₄ and CO mole fractions measured from January 2011 to April 2020 at LAN, about 50 km west of Hangzhou, 200 km southwest of Shanghai and 200 km South of Nanjing, three nearby cities bounding the conurbation where major CO₂ emissions in this part of China occur (Fig. 1). The atmospheric CO₂, CH₄ and CO mole fractions are simultaneously measured by a Cavity Ring-Down Spectrometer (CRDS; Picarro Inc USA). This instrument has been calibrated with a well-established system (Fang et al., 2013),
where the CO₂, CH₄ and CO data measured are referenced to the WMO X2007 scale (Zhao et al., 2006; Zhao et al., 1997), WMO NOAA 04 scale and 2004 scale (Dlugokencky et al., 2005., Novelli et al., 2012), respectively. Additional data processing and quality control methods are extensively documented in the previous study by Fang et al. (2015).

To obtain the contribution of regional emissions to the observed concentrations of CO₂, CH₄ and CO, this work first extracts the background concentrations using the meteorological method and robust extraction of the baseline signal (Fang et al., 2015; Ruckstuhl et al., 2010). Second the best-fit smooth curves to the background data are obtained using the methods proposed by Thoning et al (Thoning et al., 1989). Finally, the background signal is subtracted from the matching original hourly means in an attempt to compute the difference between the measurement and the background value, herein defined as \( \Delta \text{CO}_2 \), \( \Delta \text{CH}_4 \) and \( \Delta \text{CO} \) respectively (Mitchell et al., 2018). Scatter plots of \( \Delta \text{CO}_2 \) vs. \( \Delta \text{CO} \) using the hourly average values during every individual study period are made, with the slope and intercept of the best fit \( \Delta \text{CO}_2/\Delta \text{CO} \) linear regression derived and subsequently used for analysis.

Given that CO is often co-emitted along with CO₂ due to combustion (Turnbull et al., 2006; Bakwin et al., 1998; Lin et al., 2020), it has been used as an excellent tracer. In specific, the observed ratio of \( \Delta \text{CO}_2/\Delta \text{CO} \) is well recognized to be able to identify the respective contribution of fossil fuel combustion emissions and biospheric activities related to the uptake of atmospheric CO₂ (Zhang et al., 2013).

The intensive observational period (IOP) covers the period from 3 January to 20 March 2020 and is divided into 4 subperiods for the sake of subsequent analysis: pre-lockdown (IOP-1), lockdown and Chinese New Year (IOP-2), post-lockdown easing phase 1 (IOP-3), and post-lockdown easing phase 2 (IOP-4). For details of the exact days of the four IOPs, refer to Table S1. During the reference time period 2011–2019, the time origins in all figures, unless noted otherwise, are set as the Chinese Lunar New Year (CNY) to form a valid comparison with the time used when strict lockdown measures were implemented for the COVID-19 lockdown period in 2020. This is because CNY is known to be a period of time when many businesses suspend work for a 1 to 2 week long holiday and many people leave heavily developed urban areas like the YRD and head to their family homes/villages elsewhere, leading to a known decrease in emissions in large conurbations (Huang et al., 2012).

2. Results and discussion

2.1. Temporal evolution of \( \Delta \text{CO}_2 \), \( \Delta \text{CH}_4 \) and \( \Delta \text{CO} \)

Fig. 2 shows the time series of daily average \( \Delta \text{CO}_2 \), \( \Delta \text{CO} \), \( \text{CO}_2/\text{CO} \) and \( \Delta \text{CH}_4 \) during the four IOPs computed using all data from 2011–2019 and data only from 2020 respectively. As a whole, the day-by-day variation dominated for both \( \Delta \text{CO}_2 \) and \( \Delta \text{CO} \) in 2020, which showed an almost completely in-phase temporal variation pattern. Nevertheless, the temporal variation of the ratio of \( \Delta \text{CO}_2/\Delta \text{CO} \) was found to be out of phase with the variations of both \( \Delta \text{CO}_2 \) and \( \Delta \text{CO} \) due to the larger vibration in \( \Delta \text{CO} \). During IOP-1, elevated \( \Delta \text{CO}_2 \) occurred in more days in 2020 as compared with the period from 2011–2019, suggesting the year-on-year increase in emission was not different from the other year-on-year changes. This can be partly supported by provincial CO₂ emission inventories for China published by Shan et al. (2018; 2020), which followed the Intergovernmental Panel on Climate Change (IPCC) emissions accounting method (Fig S1 in the supplementary material). When summing up the CO₂ emissions for all sectors over Anhui, Zhejiang, Jiangsu province and Shanghai, the amount keep increasing from 2011 to 2017, except the decline in 2016. Higher \( \Delta \text{CO} \) were observed in nearly half of the days in IOP-1, partly attributed to the reduced or negative growth rate in CO emissions due to improved energy efficiency which has been widely reported (Zheng et al., 2018). For \( \Delta \text{CH}_4 \), higher values were observed in most days in 2020 than the historic period, but not as many as \( \Delta \text{CO}_2 \). The CH₄ emissions provided by EDGARv6.0 (https://edgar.jrc.ec.europa.eu/dataset_ghg60fp1) shows the increasing trend in CH₄ emissions. The gridded data were extracted for the area of 27.5°–34°N by 118.5°–122°E, which basically covers Yangtze River Delta of China. Furthermore, notable is the stronger fluctuations of \( \Delta \text{CO}_2 \) and \( \Delta \text{CO} \) during IOP-1 than during the subsequent IOPs, which were due to a combination of meteorological variability and an even increasing and more variable emissions profile due to the deepening and constant change of the economy as it continued to both increase and deepen year-on-year, as compared to the lockdown, which forced many industrial and commercial emissions sources to go offline or scale back significantly. For instance, persistent low-level clouds observed above LAN (not shown) during the last four days (20–23 January 2020) of IOP-1 could at least account for the evident spikes of \( \Delta \text{CO}_2 \), \( \Delta \text{CO} \) and \( \Delta \text{CH}_4 \) from a perspective of the cloud based reduction of solar radiation reaching the ground surface during daytime, thereby suppressing the planetary boundary layer (PBL) and leading to more accumulation of air pollution and CO₂. Additionally, another non-negligible factor could be the enhanced emissions induced from more intensive traffic as well as a flurry of last-minute activities in the industrial space as many final orders are rushed just before CNY.

During IOP-2, sharp drops in \( \Delta \text{CO}_2 \) and \( \Delta \text{CO} \) compared to IOP-1 were observed in both 2011–2019 and 2020, with the latter period experiencing an even larger magnitude of reduction. Significant differences exist between IOP-1 and IOP-2 at the 95% confidence level when applying the t-test for both 2011–2019 and 2020. The decrease in 2011–2019 was mainly due to decreased economic activity and travel that both occur during the CNY holiday (Ding et al., 2013), while the lower than climatological mean concentration observed in 2020 reflected a larger than normal reduction in fossil fuel activity consistent with the lockdown associated with COVID-19. Among them, evident reduction occurred in the later stage when forced confinement and lockdown protocols were strictly implemented, including social distancing and home quarantine, the shutting down of all unnecessary industries, and restriction of transportation both inter-city and intra-city.

During IOP-3, gradual recovery of \( \Delta \text{CO}_2 \) and \( \Delta \text{CO} \) were observed during the 2011–2019 period, associated with the end of the CNY holiday and a slow return to economic activity. There is significant difference between IOP-2 and IOP-3 in
By comparison in 2020 low ΔCO₂ and ΔCO continued in the first 13 days of IOP-3 as the lockdown measures continued. During this period, most industries were still closed, even though a staged resumption policy was deployed. However, ΔCO₂ and ΔCO were observed to increase gradually during IOP-4 of 2020 with the successful implementation of the staged resumption of economic activity policy.

Box plots of ΔCO₂, ΔCO, ΔCH₄, ΔCO₂/ΔCO slope and intercept during the four IOPs are shown in Fig. 3. During 2011–2019, the average concentrations of ΔCO₂, ΔCO and ΔCH₄ decreased from 3.0 ppm, 160.6 ppb and 12.5 ppb in IOP-1 to 0.8 ppm, 68.1 ppb and 0 ppb in IOP-2, then increased to 6.2 ppm, 114.7 ppb and 18.7 ppb in IOP-3, and ultimately reduced to 5.6 ppm, 64.8 ppb and 16.1 ppb in IOP-4, respectively. The
one-trough mode was mainly due to the significant reduction in anthropogenic activities during the CNY holiday (IOP-2) (Ding et al., 2013), and the slight variation in $\Delta CO_2$, $\Delta CO$ and $\Delta CH_4$ as the time transitioned from IOP-3 to IOP-4 was probably due to high frequency changes in synoptic events, short-term changes in industrial and transportation emissions, or changes in the uptake of terrestrial ecosystems (Wang et al., 2007; Peters et al., 2017; Wang et al., 2021; Deng et al., 2021). Furthermore, the lower $\Delta CO_2/\Delta CO$ slope and higher $\Delta CO$ during IOP-1 relative to post-CNY period (i.e., IOP-3 and IOP-4) was partly attributed to the high transportation emissions from "spring travel rush" in the beginning of the CNY hol-
day, as emissions sources from transportation often lead to lower $\triangle CO_2/\triangle CO$ compared to large, efficient power plants (Turnbull et al., 2011; Wang et al., 2010). This can be further corroborated by the lower $\triangle CO_2/\triangle CO$ ratio during IOP-2, which could be caused by the drop of emission from industry-sector during CNY (Liu et al., 2020; Zheng et al., 2018). Besides the contribution of emission recovery from industry-sector, the increase in $\triangle CO_2/\triangle CO$ slope from IOP-2 to IOP-4 was also partly attributed to the reduction of low efficiency domestic heating sources with the growing temperature, as well as less efficient smaller or individual industrial workshops which are also less efficient in general, which had a tendency to not re-open, or to upgrade after the end of the holiday period.

On average, the $\triangle CO_2$ (17.6 ppm), $\triangle CO$ (189.7 ppb) and $\triangle CH_4$ (29.0 ppb) during IOP-1 of 2020 were higher than the climatological means for the period 2011–2019, indicative of the constantly increasing CO2 emissions over the YRD as economy continued to grow (Wang et al., 2010; Zeng et al., 2008; Shan et al. 2018; Shan et al. 2020; Zheng et al., 2020). Likewise, the much higher $\triangle CO_2/\triangle CO$ slope (59.9) in IOP-1 compared to 29.7 during 2011–2019 suggested much higher combustion efficiency, which to some extent reflected the Chinese government’s efforts on the adjustment of energy structures and novel technology application for improving combustion efficiency (Demirbas, et al., 2009; Zheng et al., 2018). This is supported by the recent implementation of China’s State VI emission standards—reducing stringent vehicles emission standards—which became effective as of July 2019 in Hangzhou (Xinhua Net. 2020), leading to a consistent result with the observed $\triangle CO_2/\triangle CO$ ratios (Bishop and Stedman, 2008). The higher $\triangle CO_2/\triangle CO$ intercept compared to IOP-2, IOP-3 and IOP-4 implied the higher net effect of biogenic sources and sinks in the YRD region, which was attributed to enhanced ecosystem respiration due to exceptionally high temperature seen in January of 2020 (Rustad et al., 2001; Bond-Lamberty and Thomson, 2010). During IOP-2, larger reductions in $\triangle CO_2$ (15.0ppm), $\triangle CO$ (146.8 ppb) and $\triangle CH_4$ (14.2 ppb) were observed in 2020 compared to last nine-year mean (Grey shading in Fig. 3), concurrent with the implementation of strict confinement which led to the reduced emissions from industry, power supplies, transportation and residential living. The reduced $\triangle CO_2/\triangle CO$ slope (42.2) indicated evident emission drop from power generation and industry. During IOP-3, even lower $\triangle CO_2$ (2.2 ppm), $\triangle CO$ (36.1 ppb) and $\triangle CH_4$ (-0.5 ppb) are observed. The higher $\triangle CO_2/\triangle CO$ slope (67.6) reflects the synthesis impact of gradual recovery of production and power plants concerning residential energy use and persistent drop of emission from transportation (Liu et al., 2020). The significantly low $\triangle CO_2/\triangle CO$ intercept suggested the strong net sink of terrestrial ecosystem through photosynthesis. During IOP-4, all enterprises necessary for life were resumed, $\triangle CO_2$ (6.5 ppm), $\triangle CO$ (72.4 ppb) and $\triangle CH_4$ (10.8 ppb) gradually increased to the levels similar to the last nine-year climatology mean. The increase in $\triangle CO_2/\triangle CO$ slope suggests the rebound of industries with the ease of quarantine controls in China.

2.2. Diurnal variations of $\triangle CO_2$ during four IOPs

Fig. 4 shows the diurnal cycle of $\triangle CO_2$ in 2011–2019 and 2020 during the four different IOPs. The first observation is that this time cycle is mainly driven by the diurnally varying local sources/sinks and dynamics of the PBL (Bakwin et al., 1998). Overall, the trough in terms of $\triangle CO_2$ values occurred at 1300–1500 LST when the PBL grew to the maximum depth by strong turbulent transport processes (Li et al., 2017; Guo et al., 2020), thereby leading to the greatest dampening of surface CO2 fluxes. Meanwhile, the net uptake of CO2 occurred at noon when the removal of CO2 by photosynthesis that became active exceeded respiration from the terrestrial ecosystem. These findings are consistent with basic theory and add support to the idea that the measurements are valid and consistent. Henceforth any significant changes as discussed were likely not due to the placement of the measurement sites or other non-linear effects associated with an improper coverage.

Interestingly, the diurnal cycles of $\triangle CO_2$ exhibited a pattern with two-peaks and one-trough, irrespective of 2011–2019 and 2020. One peak occurred around sunrise (0600–0900 LST), which corresponded to rush hour when intensive traffic emissions occurred. The other peak happened in the midnight (2400–0300 LST), when the net sources from vegetation respiration happened at roughly the same time as the most stable and shallow PBL. Between the first peak and the trough, $\triangle CO_2$ gradually decreased from sunrise to midday when the rapid growth of PBL diluted CO2 by drawing in fresh air from aloft. Between the trough and the second peak, $\triangle CO_2$ gradually increased after sunset as emissions filled the shallow nighttime PBL.

As expected, during IOP-1 of 2020, hourly mean $\triangle CO_2$ throughout the course of day was much higher than in the same period of 2011–2019. During IOP-2, hourly mean $\triangle CO_2$ decreased in both 2011–2019 and 2020, compared to IOP-1, with the largest decline occurring in 2020, reflecting the dramatic impact of lockdown measures. During IOP-3, an upturn in $\triangle CO_2$ was observed for the diurnal readings in 2011–2019, suggesting a recovery of CO2 emission from fossil fuels combustion with the end of CNY holiday. While in 2020, $\triangle CO_2$ kept declining during most of time, much lower in general than as observed in 2011–2019, indicating the persistent impact of low CO2 emission due to quarantine measurements. During IOP-4, average CO2 increased throughout all hours in 2020, increasing to similar levels as the climatological mean, suggesting the impact of alleviation of quarantine measures in China, although possibly on a slightly lower planetary background due to increasing reductions in economic activity elsewhere.

2.3. Potential impact of meteorological variables

It is well documented that meteorological conditions have effects on the surface CO2 through diffusion and mixing processes (Bischof et al., 1980; Haszpra et al., 2012). Here, the meteorological variables related to the vertical satiability
Fig. 4 – Hourly mean of $\Delta$CO$_2$ in 2011–2019 (blue) and 2020 (red) during IOP-1 (a), IOP-2 (b), IOP-3 (c) and IOP-4 (d). The bands are 95% confidence intervals of each hour.

and horizontal diffusion were used, including boundary layer height (BLH), lower tropospheric stability (LTS) and wind speed (WS). BLH, to some extent, affects the dilution of near-surface pollutants mainly through vertical convection and turbulence mixture (Nair et al., 2018; Lou et al., 2019). LTS is defined as the difference in potential temperature between 700 hPa and the surface (Slingo, 2007), which can be used to determine the thermodynamic state of the lower troposphere (Guo et al., 2016). WS is recognized to be able to dictate the horizontal advection of air masses. The association of daily mean BLH, LTS and WS with $\Delta$CO$_2$ was analyzed only during two time periods each day: from 1200 to 1600 LST (the time period when the strongest convection and turbulence occurred) and from 2300 to 0300 LST (the time period when the stable PBL dominated), respectively. The strongest correlations were found in the afternoon (1200–1600 LST). Time series of daily mean BLH, LTS and WS during 1200–1600 LST and $\Delta$CO$_2$ anomalies relative to 2011–2019 are plotted in Fig. 5. Among all factors, BLH was most correlated with $\Delta$CO$_2$ anomalies ($R = -0.40$), followed by WS ($R = -0.27$) and LTS ($R = 0.19$). Averaged WS ($R = -0.26$) and LTS ($R = 0.15$) during 2300–0300 LST were also found correlated with $\Delta$CO$_2$ anomalies (data not shown). The anti-correlations between BLH/WS and $\Delta$CO$_2$ suggested that higher BLH and WS reinforced vertical dilution and horizontal dispersion of CO$_2$, respectively, and consequently led to reduced CO$_2$ (Yi et al., 2000). The positive relationship between LTS and $\Delta$CO$_2$ indicated the stable lower troposphere dampened the diffusion of surface CO$_2$ efflux. However, the individual correlation values were considered relatively small, warranting further discussion of the real-world application of the general theory to high-frequency measurements.

From IOP-1 to IOP-4, the average LTS gradually decreased, while BLH and WS generally increased except for a slight decrease in BLH from IOP-2 to IOP-3. In such case, one explanation for the evidently higher $\Delta$CO$_2$, $\Delta$CO and $\Delta$CH$_4$ during IOP-1 is the weaker atmospheric advection and entrainment indicated by low BLH/WS and high LTS. The wind field at 850 hPa (Fig. S1 in Appendix A) shows that the low-level winds are mostly from southwest, bringing air pollution from southern China and Continental Southeast Asia. During IOP-2, the reduced CO$_2$ was partly attributed to more diffusion by entrainment of fresh air from above with rise in WS/BLH and decline in LTS. Contrarily, there were other atmospheric circulation tends that tended to increase CO$_2$ at the receptor site as due to the following aspects. Firstly, the decrease in geopotential height at 500 hPa (CH$_{500hPa}$) suggested stabilizing lower tropo-
spheric circulation. Secondly, the wind field at 850 hPa indicates that the air masses that passed over this region in large part derived from the sea region to the northeast of Shanghai and subsequently passed over the background measurement station, providing ample ability to sample the impacts of emissions changes from the megacity core. During IOP-3, WS and LTS were favorable for mixing, which could result in the decrease in CO₂, as well as the possible mixing in of enhanced CO from above due to long-range transport of sources from Southern China and/or Southeast Asia. This is further consistent with the increase in GH₃00hPa also indicating strong local convection. Similarly, the wind field indicated the influence of long-range transport from central China with slow speed. By contrast, a slight decrease in BLH could lead to suppressed vertical mixing and the consequent buildup of CO₂. During IOP-4, increased BLH/WS and reduced LTS were generally linked to growing vertical advection. Besides, enhanced GH₃00hPa also supported strong convection. Nevertheless, the observed CO₂ increase suggested that the recovery in CO₂ was dominated by the emission increase from socioeconomic activities recovery. Moreover, the wind field showed more influence from Northern China, a region with intensive industries. These results are all consistent with the observed economic recovery in northern China.

The ΔCO₂ segregated by horizontal wind direction were also studied (Fig. S2 in Appendix A). The impact of the control measures can be found from the different patterns between 2020 and 2011–2019. During the period 2011–2019, the winds from the ENE-E-SEE sectors were generally accompanied with higher CO₂ during all periods, due to abundant emission sources in the mega-conurbation existing from Shanghai through Hangzhou and Nanjing, all located to the east through northeast. From IOP-1 to IOP-2, reduced CO₂ were observed in all directions, indicating reduced CO₂ emissions nearby due to limited human activities during CNY holiday which are known to occur throughout China. From IOP-3 to IOP-4, CO₂ from most directions were enhanced when CNY holiday ended. In 2020, higher CO₂ were observed for all wind sectors during IOP-1 compared to 2011–2019, mainly due to increasing trend of CO₂ emissions. During IOP-2, CO₂ from all wind directions largely decreased to the similar level with the climatological mean under deployment of the lockdown policy, except for the higher load under the prevailing winds from the SSW-S-SSE that corresponded to the downtown areas of LAN. The weak COVID signal in small town reflected the emissions reductions are concentrated mainly in industrialized regions and areas, which is consistent with the baseline of required emissions for power generation, water distribution, medical use, etc. were not as impacted as industrial and transport emissions. During IOP-3, reduced CO₂ was observed in all directions except for E-SEE, generally corresponding to the Hangzhou conurbation, compared to both IOP-2 in 2020 and climatological mean, reflecting the recovery of factories in Hangzhou under staged resumption policy. During IOP-4, the CO₂ from all directions were observed similar to climatological mean, suggesting that socioeconomic activities surrounding LAN gradually recovered to the normal state in 2011–2019.

3. Summary and conclusions

In this study, the influence of emission reductions during the COVID-19 lockdown on atmospheric CO₂, CH₄ and CO in China was comprehensively investigated. Larger reductions in ΔCO₂, ΔCO and ΔCH₄ than 2011–2019 were observed from IOP-1 to IOP-2, consist with the remarkable emission reduction in fossil fuel combustion and industrial sources due to the confinement measures. Large reduction in ΔCO₂/ΔCO slope during
IOP-2 indicates the prohibition of high efficiency combustion like industries combined with a larger CO₂ uptake connected to the enhanced temperature and less anthropogenic disturbance associated with the lockdown, and possibly higher CO sources due to long-range transport from activities occurring in Southern China or Southeast Asia. The increase in ΔCO₂/ΔCO slope during IOP-3 suggests gradual recovery of CO₂ emission from industries and delayed drop CO₂ emission from transportation. The continuous decrease in ΔCO₂, ΔCO and ΔCH₄ during IOP-3 were attributed in part to a strong net sink of terrestrial ecosystem uptake through photosynthesis (which was enhanced in part due to the lockdown) and continuous decrease in CO₂ emissions from fossil fuel combustion in the vicinity of LAN except for the large combustion from Hangzhou to Shanghai and Nanjing. During IOP-4, ΔCO₂, ΔCO and ΔCH₄ increased to the level similar to the climatological means, implying the more robust and widespread recovery of anthropogenic activities under relaxed public health policies in China. The diurnal variability was also affected during the lockdown period. The ΔCO₂ hourly mean declined throughout the day during IOP-2 and during most of time in IOP-3, and subsequently recovered during IOP-4. CO₂ was found negatively correlated with BLH/WS and positively correlated with LTS, respectively. GHG₀thpa, and wind direction were shown to have an influence on the near-surface CO₂.

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Appendix A Supplementary data

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.jes.2021.09.034.

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