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Spatiotemporal variations and reduction of air pollutants during the COVID-19 pandemic in a megacity of Yangtze River Delta in China

Qi Yuan, Bing Qi, Deyun Hu, Junjiao Wang, Jian Zhang, Huanqiang Yang, Shanshan Zhang, Lei Liu, Liang Xu, Weijun Li

Key Laboratory of Geoscience Big Data and Deep Resource of Zhejiang Province, Department of Atmospheric Sciences, School of Earth Sciences, Zhejiang University, Hangzhou 310027, China
Hangzhou Meteorological Bureau, Hangzhou 310051, China

HIGHLIGHTS

• Significant improvement of air quality during the COVID-Lock period in Hangzhou
• 80% reduction of NOx and double increase of O3 during the COVID-Lock period
• Daytime 30% reduction of air pollutant due to elevation of planetary boundary layer
• Large contribution of regional fine particle during long-range transport events

GRAPHICAL ABSTRACT

Abstract

In recent decades, air pollution has become an important environmental problem in the megacities of eastern China. How to control air pollution in megacities is still a challenging issue because of the complex pollutant sources, atmospheric chemistry, and meteorology. There is substantial uncertainty in accurately identifying the contributions of transport and local emissions to the air quality in megacities. The COVID-19 outbreak has prompted a nationwide public lockdown period and provides a valuable opportunity for understanding the sources and factors of air pollutants. The three-month period of continuous field observations for aerosol particles and gaseous pollutants, which extended from January 2020 to March 2020, covered urban, urban-industry, and suburban areas in the typical megacity of Hangzhou in the Yangtze River Delta in eastern China. In general, the concentrations of PM2.5, PM10, NOx, SO2, and CO reduced 58%, 47%, 83%, 11% and 30%, respectively, in the megacity during the COVID-Lock period. The reduction proportions of PM2.5 and CO were generally higher in urban and urban-industry areas than those in suburban areas. NOx exhibited the greatest reduction (>80%) among all the air pollutants, and the reduction was similar in the urban, urban-industry, and suburban areas. O3 increased 102%–125% during the COVID-Lock period. The daytime elevation of the planetary boundary layer height can reduce 30% of the PM10, PM2.5, NOx and CO concentrations on the ground in Hangzhou. During the long-range transport events, air pollutants on the regional scale likely contribute 40%–90% of the fine particles in the Hangzhou urban area. The findings highlight the future control and model forecasting of air pollutants in Hangzhou and similar megacities in eastern China.

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1. Introduction

In the past decade, air pollution has become a major environmental problem in eastern China, and air quality has been continuously improved via the implementation of multiple control measures in recent years (Guo et al., 2019; Ma et al., 2019). Mass concentrations of PM$_{10}$, PM$_{2.5}$, SO$_2$, and CO decreased 13.6%–30.5% from 2015 to 2017 based on observation data from 366 cities of mainland China (Guo et al., 2019). However, due to the high energy consumption and explosive growth of vehicular traffic, air pollution is still an important environmental problem in rapidly expanding cities, such as the megacities in the developed Yangtze River Delta (YRD) in eastern China (Ming et al., 2017; Zhang et al., 2018).

Hangzhou, which is the second largest city in the YRD and the capital city of Zhejiang province, is a typical new and template city with rapid urbanization, a high population growth rate and a rapid increase in the number of vehicles in eastern China. The urbanization process, industrial structure, traffic distribution and environmental protection can represent the development direction of many cities in eastern China. It is representative and instructive for similar cities to conduct research on the sources and characteristics of aerosol particles (i.e., PM$_{10}$ can represent the development direction of many cities in eastern China, and its high infectivity strongly threatened human health (Huang et al., 2017; Zhang et al., 2018).

Several studies focused on the assessment of control strategies for air pollution reduction during some mega-events, such as the World Internet Conference in 2015 and the G20 summit in 2016, which were held in Hangzhou (Feng et al., 2018; Ji et al., 2018; Li et al., 2018; Ni et al., 2018). A study from the WRF-Chem model showed that long-range transport contributed 30%–85% of PM$_{2.5}$ in Hangzhou (Ni et al., 2018). The WRF-Chem model combined with field observations showed that local emissions contributed more than 50% of PM$_{2.5}$ in Hangzhou (Shu et al., 2019). The WRF/CMAQ model results indicated that local emission sources accounted for 15.8%, 68.6%, 48.3% and 59.2% of the overall concentrations of SO$_2$, NO$_x$, PM$_{2.5}$ and PM$_{10}$, respectively, in Hangzhou (Feng et al., 2018). In addition to the model work, there is still a lack of field observation data for quantifying the contribution of local emissions and transport in Hangzhou (Sun et al., 2018; Zhang et al., 2020c).

A novel coronavirus named "COVID-19" accidentally appeared in Wuhan city in late December 2019 (Chen et al., 2020; Wu et al., 2020) and its high infectivity strongly threatened human health (Huang et al., 2020a; Xu et al., 2020). The Chinese government took powerful timely actions to control the spread of the virus, such as the highest epidemic emergency response, community lockdown, traffic restrictions, and factory shutdowns. These effective actions stopped people from gathering and successfully reduced the risk of the novel coronavirus infection. Note that this public health emergency not only locked down people in the community but stopped the operation of the public traffic system and industry machine, which caused a short-term regional reduction of air pollutant emissions from vehicles and some industries in China (Huang et al., 2020b; Shi and Brasseur, 2020; Zambrano-Monserrate et al., 2020; Zheng et al., 2020). The National Aeronautics and Space Administration (NASA) and European Space Agency (ESA) pollution monitoring satellites detected an approximately 65% decrease in NO$_2$, and the Copernicus Atmosphere Monitoring Service (CAMS) detected an approximately 20%–30% decrease in PM$_{2.5}$ over the majority of China (CAMS, 2020; NASA, 2020). The strictest nationwide restrictions for preventing the COVID-19 spread greatly reduced the primary emissions and weakened the regional transport effect of air pollutants due to the large-scale regional decrease in the primary pollution (Huang et al., 2020b; Zhang et al., 2020b). Consequently, the pandemic incident becomes a special atmospheric research hotspot due to the dramatic reduction in anthropogenic emissions (Bauwens et al., 2020; Le et al., 2020; Sun et al., 2020). This special period offers us a unique opportunity to accurately assess how the reduction in local emissions influences the air quality in megacities (Li et al., 2020).

In this study, we systematically analyzed the continuous three-month data of particulate and gaseous pollutants at one urban site, three urban-industry sites and six suburban sites in Hangzhou. To better understand the variation and reduction in air pollutants, we classified the measurement periods into pre-COVID, Chinese New Year (CNY), COVID-19 lockdown (COVID-Lock), COVID-Recover-I, and COVID-Recover-II from 1 January 2020 to 31 March 2020. We found a significant reduction in PM$_{2.5}$–10, PM$_{2.5}$, NO$_x$, SO$_2$, CO and an increase in O$_3$ during the COVID-Lock period. This study preliminarily reveals the contribution of transport and local emissions in a typical urban area in the YRD. The findings provide a reference for future air pollution control in the megacities in eastern China.

2. Material and methods

2.1. Observation sites

Hangzhou is located in the southern region of the YRD and the middle of eastern China with an area of 16,853 km$^2$ and a large population of ~8 million (Fig. 1 and Table S1). All ten observation sites cover the urban area (Hangzhou-HZ), urban–industry area (Xiaoshan-XS, Linjiang-LJ, and Yuhang-YH), and suburban area (Chunan-CA, Fuyang-FY, Xindeng-XD, Jiande-JD, Linan-LA, and Tonglu-TL). (Fig. 1 and Table S1). The urban and urban-industry sites are located in the east low plain area, and the suburban sites are mostly located in the middle and west mountain areas (Fig. 1). The urban site is located in the city center with the largest population density and more than 2 million vehicles (Table S1). The urban-industry sites are located in the industry districts with a total of more than 2600 enterprises and nearly 1 million vehicles (Table S1). Ecotourism is one of the major domains in the suburban area due to the better ecological environment and air quality of this area. Fig. 1 shows that the major stationary emissions of air pollutants (i.e., PM$_{10}$, PM$_{2.5}$, NO$_x$, and SO$_2$) in Hangzhou distribute in the urban-industry area. As a result, we determined that the air quality in the urban and urban-industry areas are worse than that in the suburban area (Table S1). These monitoring sites, which comprise different locations and environments, can represent the different air quality in Hangzhou city.

2.2. Mass concentration observations of particle and gaseous pollutants

PM$_{2.5}$ and PM$_{10}$ mass concentrations were measured by the Model 5030 Synchronized Hybrid Ambient Real-time Particulate (SHARP) Monitor (Thermo Fisher Scientific, USA). SO$_2$ was measured by a Pulsed Fluorescence SO$_2$ Analyzer (Model 43i, Thermo Environmental Instruments Inc. USA). NO$_x$ was measured by a commercial NO-NO$_2$-NO$_x$ chemiluminescence analyzer coupled with an internal MoO$_3$ catalytic converter (Model 42i, Thermo Environmental Instruments Inc. USA). CO was measured by a Gas Filter Correlation CO Analyzer (Model 48i, Thermo Environmental Instruments Inc. USA). O$_3$ was measured by a UV Photometric O$_3$ Analyzer (Model 49i, Thermo Environmental Instruments Inc. USA). The multipoint calibration for gaseous analyzers was performed each week.

Meteorological data, including the relative humidity (RH), temperature (T), wind speed (WS), wind direction (WD) and precipitation amount, were measured by automatic meteorological stations managed by the Hangzhou Meteorological Bureau. Visibility (Vis) was detected by a visibility sensor (PW10, Vaisala, Netherlands).

2.3. Observation period division

Our field observations were conducted from 1 January 2020 to 31 March 2020. Based on the local investigation in Hangzhou city, we identify several important date nodes, such as 24 January (CNY’s Eve), 4 February (first day of the strictest lockdown in Zhejiang province), 19 February (first day of the resumed operation of the traffic system in
Hangzhou, Fig. S1), and 2 March (first day of the downgraded epidemic emergency response in Zhejiang province).

2.3.1. Pre-COVID period (1 January to 23 January 2020)

The novel coronavirus in Hubei province was not confirmed as the epidemic. The industry operation and traffic continued normal operations in most regions in China during this period. The traffic performance index (TPI, Fig. S1) was a suitable index for indicating the traffic flow, and TPI ≥ 4 indicated the traffic jam. The average TPI was 2 during the pre-COVID period in the urban area in Hangzhou and exceeded 4 in 14% of the time (Fig. S1). The highest epidemic emergency response in Zhejiang province began on 23 January.

2.3.2. CNY vacation (24 January to 3 February 2020)

There was very low traffic flow (TPI = 0.13) and few industries maintained normal operation due to the novel coronavirus epidemic, but large amounts of fireworks were burned in the suburban area. According to the official bans, fireworks were only allowed in the suburban areas in megacities during the CNY.

2.3.3. COVID-lock period (4 February to 18 February 2020)

The strictest epidemic prevention and control policies were issued in Zhejiang Province, and the control policies encompassed the whole country in the following two days. Most regions in China were in a lockdown state and all the traffic systems among the villages, cities and provinces were shut down. The TPI decreased to nearly zero (0.06) during the COVID-Lock period (Fig. S1). According to the statistics of the Hangzhou Development Commission, almost less than 1% of enterprises continued normal operations at the beginning of the COVID-Lock period, and approximately 70% of enterprises resumed on 18 February.

2.3.4. COVID-recover-I period (19 February to 1 March 2020)

All the city-level highways resumed, and open-air public places were open for people since 19 February. The traffic system resumed, and the average TPI was 0.25 in the urban area (Fig. S1). Nearly 100% of enterprises resumed operation during this period according to the statistics of the Hangzhou Development Commission.

2.3.5. COVID-recover-II period (2 March to 31 March 2020)

The epidemic emergency response in Zhejiang province was downgraded beginning on 2 March. The industry operation returned to normal, and the traffic system was further recovered (TPI = 0.9).

2.4. Transport event identification

Concentration-weighted trajectory (CWT) analysis, which is based on the backward trajectory, can be employed to identify the transport event and estimate the contribution of air pollutants from different regions (Zhang et al., 2020a). In this study, 72-h air mass backward trajectories with one-hour resolution were calculated with an ending height of 500 m above ground level based on the meteorological data sets from the Nation Oceanic Atmospheric Administration (NOAA) (ftp://arlftp.arlhq.noaa.gov/pub/archives/gdas1). The user-friendly Igor-based tool “ZeFir”, which was developed by Petit et al. (2017), was utilized for CWT analysis. The region covered by the CWT analysis consists of thousands of cells with a resolution of 0.2° × 0.2°.
3. Results

3.1. Overall characteristics of air pollutants and meteorological conditions

During the observation period, the daily average mass concentrations of PM$_{10}$, PM$_{2.5}$, NO$_x$, SO$_2$, CO, and O$_3$ in Hangzhou were 49.9 μg/m$^3$, 32.2 μg/m$^3$, 29.1 μg/m$^3$, 5.1 μg/m$^3$, 929.1 μg/m$^3$, and 46.8 μg/m$^3$, respectively. The mass concentrations of PM$_{10}$ and PM$_{2.5}$ exceeded the daily average Grade I values (50 μg/m$^3$ and 35 μg/m$^3$) of the Ambient Air Quality Standard of China (CAAQS, GB 3095-2012) during approximately 1/3 of the total observation period. There were six peaks of particle pollutants that could be affected by the long-range transport according to the observation record and meteorological conditions (Fig. 2). The mass concentrations of SO$_2$ and CO were always substantially lower than the daily average Grade I values (50 μg/m$^3$ and 4000 μg/m$^3$) of the CAAQS on each day (Fig. 2). The mass concentrations of NO$_x$ exceeded the daily average Grade I values (100 μg/m$^3$) of the CAAQS on 1–3 days (Fig. 2). The mass concentrations of O$_3$ exceeded the hourly average Grade I values (160 μg/m$^3$) of the CAAQS in only 1–4 h (Fig. 2). These results suggest that the air quality in Hangzhou was generally satisfactory from January to March 2020 due to the strict control measures for COVID-19. The mass concentrations of PM$_{2.5}$, NO$_x$, and CO at the urban site were higher than those at the urban-industry and suburban sites (Table S2), which suggests that vehicle emissions was the major source of air pollutants in the urban area. The weather conditions were mostly stable with low wind speeds (<3 m/s) and high RH (~77%) during the observation period (Fig. 2).

3.2. Air quality improvement during the COVID-lock period

To evaluate the reduction in air pollutants during the COVID-Lock period, the temporal variations in the six air pollutants (i.e., PM$_{2.5}$–10, PM$_{2.5}$, NO$_x$, SO$_2$, CO, and O$_3$) are compared among the urban, urban-industry and suburban sites during different periods (Figs. 3, S2 and S3).

(a) PM$_{2.5}$–10

During the COVID-Lock period, the average PM$_{2.5}$–10 mass concentrations at the urban site, urban-industry site, and suburban site were 8.5 μg/m$^3$, 11.5 μg/m$^3$, and 7.0 μg/m$^3$, respectively, which decreased 54%, 62%, and 58%, respectively, compared with those during the pre-COVID period (Figs. 3a and S2a). Coarse particles (PM$_{2.5}$–10) in the megacities of eastern China are mainly dominated by man-made fugitive dust from construction activities and roads, natural dust from the ground, growth of secondary aerosol particles, and industrial activities in urban areas (Guo et al., 2020). A higher reduction proportion of the coarse particles occurred at the urban-industry sites than that at the urban and suburban sites, which suggests that man-made dust particles from construction and industry activities largely contributed to the coarse particles in the urban-industry areas. Because the Asian Game of 2022 will be hosted in the urban-industry area (Xiaoshan and Linjiang), a considerable number of intense construction activities occurred in the urban-industry areas of Hangzhou, including stadium, road and subway construction, before the CNY. As shown in Fig. 1a, numerous industries with large amounts of PM$_{10}$ emissions (200–500 t per year) are located in the urban-industry area and contribute to the coarse particles under normal production during the pre-COVID period.

(b) PM$_{2.5}$

During the COVID-Lock period, the average PM$_{2.5}$ mass concentrations at the urban site, urban-industry site, and suburban site were 24.9 μg/m$^3$, 23.0 μg/m$^3$ and 22.8 μg/m$^3$, respectively, which decreased 59%, 54% and 42%, respectively, compared with those during the pre-COVID period, respectively (Figs. 3b and S2b). The industrial and vehicle emissions have been suggested to be the major sources of fine particles in Hangzhou (Feng et al., 2018; Wu et al., 2016). The obvious reductions of PM$_{2.5}$ were direct responses to the strict lockdown actions, and the majority of fine particles from industry and traffic emissions were...
eliminated during the COVID-Lock period (Figs. S1 and S2). The low correlations (Fig. S3, urban: 0.42, urban-industry: 0.39, suburban: 0.45) between PM$_{2.5}$ and CO suggest that the primary emissions from industrial and traffic emissions decreased with an increase in secondary particles in PM$_{2.5}$ during the COVID-Lock period.

(c) NO$_x$

During the COVID-Lock period, the average NO$_x$ ($NO_x = NO + NO_2$) concentrations at the urban site, urban-industry site, and suburban site were 12.2 µg/m$^3$, 10.0 µg/m$^3$ and 7.0 µg/m$^3$, respectively, which decreased 82%, 83%, and 83%, respectively, compared with those during the pre-COVID period (Figs. 3c and S2c). NO$_x$ exhibited the largest decrease among the six air pollutants, which is approximately 1.4, 1.6, 6.2 and 2.6 times the reduction proportion of PM$_{2.5-10}$, PM$_{2.5}$, SO$_2$ and CO. The dramatic reduction further proves that vehicle emissions was the major source of NO$_x$ in Hangzhou because the lockdown policy effectively controlled traffic.

(d) SO$_2$

Fig. 3. Increase in proportion of (a) PM$_{2.5-10}$, (b) PM$_{2.5}$, (c) NO$_x$, (d) SO$_2$, (e) CO, and (f) O$_3$ mass concentration during the CNY, COVID-Lock, COVID-Recover-I, and COVID-Recover-II periods versus the pre-COVID period at different observation sites.
During the COVID-Lock period, the average SO2 concentrations at the urban site, urban-industry site, and suburban site were 970 μg/m³, 678 μg/m³, and 803 μg/m³, respectively, which decreased 22%, 33%, and 25%, respectively, compared with those during the pre-COVID period (Figs. 3f and S2f). SO2 control was effective on normal days, and the average reduction proportion of SO2 was the lowest among all the air pollutants. Emissions of industrial and coal-fired power plants are the major sources of SO2 in Zhejiang province (Zhang et al., 2018). We noticed that the slight increase in SO2 concentrations occurred during the COVID-Recover-II period due to the higher production intensity than that during the pre-COVID period, which made up the production shortage during the COVID-Lock period in China. The slight reduction in SO2 indicates that some heavy industries and coal-fired power plants were still operational during the COVID-Lock period.

During the COVID-Lock period, the average CO mass concentrations at the urban site, urban-industry site, and suburban site were 3.9 μg/m³, 6.2 μg/m³, and 4.0 μg/m³, respectively, which decreased 22%, 9%, and 9%, respectively, compared with those during the pre-COVID period (Figs. 3d and S2d). SO2 control was effective on normal days, and the average reduction proportion of SO2 was the lowest among all the air pollutants. Emissions of industrial and coal-fired power plants are the major sources of SO2 in Zhejiang province (Zhang et al., 2018). We noticed that the slight increase in SO2 concentrations occurred during the COVID-Recover-II period due to the higher production intensity than that during the pre-COVID period, which made up the production shortage during the COVID-Lock period in China. The slight reduction in SO2 indicates that some heavy industries and coal-fired power plants were still operational during the COVID-Lock period.

During the COVID-Lock period, the average O3 concentrations at the urban site, urban-industry site, and suburban site were 57.9 μg/m³, 59.8 μg/m³, and 49.9 μg/m³, respectively, which increased 125%, 114%, and 102%, respectively, compared with those during the pre-COVID period (Figs. 3e and S2e). Based on the highest reduction in CO concentration at the urban-industry site, industrial emissions have a greater contribution to CO in Hangzhou.

Ozone exhibited the opposite variation trend compared with other air pollutants. During the COVID-Lock period, the average O3 mass concentrations at the urban site, urban-industry site, and suburban site were 3.9 μg/m³, 6.2 μg/m³, and 4.0 μg/m³, respectively, which increased 125%, 114%, and 102%, respectively, compared with those during the pre-COVID period (Figs. 3f and S2f). Several observations show that the formation of O3 is under the VOC-limited regime in the YRD, including Hangzhou, and high concentrations of NOx can inhibit the formation of O3 (Ding et al., 2013; Zhang et al., 2018). In addition, the reduction of PM2.5 is in favor of the O3 formation (Li et al., 2019); this mechanism promotes the increase in O3 during the COVID-Lock period.

In general, the lockdown actions during the COVID-Lock period achieved obvious positive effectiveness for the air quality improvement in Hangzhou. We discover that all the air pollutants, with the exception of O3, decreased during the COVID-Lock period and the reduction proportion of each pollutant was generally higher in urban and urban-industry areas than the suburban areas. NOx exhibited the highest reduction with a maximum decrease of ~80%. O3 is the only air pollutant that exhibited an obvious increase more than 1 time during the COVID-Lock period.

### 3.3. Diurnal variations in air pollutants during the COVID-lock period

During the COVID-Lock period, a continuously low traffic flow was maintained and few industries maintained normal production. Based on the minimum continuous local and regional emissions in the YRD during the COVID-Lock period, it is an opportunity to generally evaluate the role of the planetary boundary layer (PBL) in the local air pollutants in Hangzhou. Fig. 4 shows that PM2.5, PM2.5, NOx, and CO all exhibited a significant decrease since sunrise between 7:00–8:00 in the morning. Mass concentrations of these air pollutants reached the lowest values and the highest temperature occurred from 14:00–15:00 at all the observation sites (Fig. 4a–d). The PBL height is an important meteorological factor that affects the mixing, transport, accumulation and dilution of air pollutants (Li et al., 2017; Tang et al., 2007). There is usually negative feedback between the PBL height and particle concentrations (Petaja et al., 2016), and a reduced PBL height is favorable for the accumulation of air pollutants in the weak turbulent diffusion conditions (Wang et al., 2018). The reduction rate of air pollutants by the elevation of the PBL height with an increase in temperature can be calculated via the mass concentration at sunrise (~8:00) divided by the difference between the mass concentration at sunrise (~8:00) and the minimum values at noon (12:00–14:00) (dashed line in Fig. 4a–d).

Based on this analysis, we can estimate the air quality impacted by the elevation of the PBL height in the daytime in the urban area, urban-industry area and suburban area: a reduction of 47%, 41%, and 41%, respectively, for PM2.5; a reduction of 42%, 42%, and 41%, respectively, for NOx; and a reduction of 18%, 20% and 16%, respectively, for CO (Fig. 4e). Overall, the daytime elevation of the PBL height can dilute approximately ~30% of PM2.5, PM2.5, NOx, and CO concentrations on the ground in Hangzhou.

However, we observed the opposite diurnal trends of SO2 and O3 in Hangzhou (Fig. S4), and a similar diurnal pattern has been observed in Hangzhou by Ji et al. (2018). The reason for these trends should be that power plants, as the major contributors of SO2 emissions, mainly operated during the daytime for the electricity consumption of household and industrial activities. O3 formation mainly occurred in the daytime due to the photochemical cycle in the atmosphere (Xue et al.,...
Identification of transport events and contribution rate of transport and local emission during these transport events. CWT plots of PM$_{2.5}$ before arriving at Hangzhou during (a) transport event 1 (2020/1/12 13:00 to 1/15 14:00, Beijing time), (b) transport event 2 (2020/1/20 15:00 to 1/22 16:00, Beijing time), (c) transport event 3 (2020/1/30 1:00 to 1/31 16:00, Beijing time), (d) transport event 4 (2020/2/22 17:00 to 2/23 23:00, Beijing time), (e) transport event 5 (2020/2/25 18:00 to 2/26 7:00, Beijing time) and (f) transport event 6 (2020/3/11 18:00 to 3/12 9:00, Beijing time). (g) The histogram represents the average mass concentrations of PM$_{2.5}$ and PM$_{10}$ during each transport event in the urban area of Hangzhou. The pie chart represents the contribution proportions of transport and local emissions during each transport event. The red events represent the transport events that occurred during the COVID-19 pandemic periods.

Fig. 5.
3.4. Long-range transport of air pollutants

In this study, a total of six transport events from the CWT analysis were identified during the observation period: two northern long-range transport events during the pre-COVID period (event 1: 1/12 13:00 to 1/15 14:00, event 2: 1/20 15:00 to 1/22 16:00, Beijing time), one northern long-range transport event during the CNV period (event 3: 1/30 1:00 to 1/31 16:00, Beijing time), two southern and western long-range transport events during the COVID-Recover-I period (event 4: 2/22 17:00 to 2/23 23:00, event 5: 2/25 18:00 to 2/26 7:00, Beijing time), and one northern long-range transport events during the COVID-Recover-II period (event 6: 3/11 17:00 to 3/12 09:00, Beijing time) (Fig. 5a–f).

The average PM$_{2.5}$ mass concentrations in the urban area of Hangzhou were 110 μg/m$^3$ (event 1), 102 μg/m$^3$ (event 2), 73 μg/m$^3$ (event 3), 63 μg/m$^3$ (event 4), 98 μg/m$^3$ (event 5), and 76 μg/m$^3$ (event 6) during the long-range transport events (Fig. 5g). The large increase in PM$_{2.5}$ mass concentrations during long-range transport events 1–6 suggest that the transport of fine particles significantly contributes to air pollution in Hangzhou. Fig. 5g shows the lower fine particle concentrations during the transport events in the COVID-19 pandemic periods (events 3–6) than that in the pre-COVID periods (events 1–2). Therefore, there were large reductions in the regional industry and vehicle emissions in the YRD during the COVID-19 pandemic periods.

An approximate assessment via the CWT analysis shows that the contribution proportion of transport for the fine particles in the urban area in Hangzhou was 90%, 65%, 86%, 40%, 54%, and 76% with an average of 66% during long-range transport events 1–6 (Fig. 5g). The northern long-range transport contributes a greater amount to the fine particles than the western and southern transport. The long-range transport is an important factor for air pollution in Hangzhou. The strict and effective interregional control policies should be considered in the future.

4. Summary

The COVID-19 pandemic is one of the most serious public health emergencies in recent decades. Several strict and large regional-scale policies were implemented to control the spread of virus. This study selected Hangzhou, which is a developed ecological and economic templet megacity in eastern China, to investigate the spatiotemporal variations in the aerosol particles and gaseous pollutants before and during the COVID-19 pandemic period.

Marked reductions of PM$_{2.5-10}$, PM$_{2.5}$, NO$_x$, SO$_2$ and CO were observed in Hangzhou during the COVID-Lock period, with an average reduction of 58%, 47%, 83%, 11% and 30%, respectively. Conversely, O$_3$ increased more than 1 time with the lockdown of traffic and industry. The response of air pollutants to the lockdown actions was more significant in the urban and urban-industry areas, where traffic and industry were the major sources of air pollutants. NO$_x$ was the most sensitive air pollutant in response to the reduction in the traffic and industry emissions. The PBL exhibited a more obvious dilution effect for the particle pollutants in the suburban area. We present an approximate calculation that transport contributes 40%–90% of fine particles in the urban area of Hangzhou during the long-range transport events.

Based on the three-month continuous observations, this study can serve as a general reference for future air pollution control. Cooperative control of aerosol particles, NO$_x$ and ozone will be an important issue for air quality improvement. It is important to strengthen the coordinated interregional control to reduce the transport effects.

CRediT authorship contribution statement

Qi Yuan: Writing – original draft, Methodology, Visualization, Funding acquisition, Bing Qi: Conceptualization, Resources, Supervision, Funding acquisition. Deyun Hu: Data curation, Resources. Junjiao Wang: Data curation, Resources. Jian Zhang: Methodology, Writing - review & editing. Huaqiang Yang: Data curation, Resources. Shanshan Zhang: Data curation, Resources. Lei Liu: Methodology, Writing - review & editing. Liang Xu: Methodology, Writing - review & editing. Weijun Li: Conceptualization, Supervision, Funding acquisition.

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

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