



Air-pollutant mass concentration changes during COVID-19 pandemic in Shanghai, China

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Abstract

To curb the spread of the coronavirus, China implemented lockdown policies on January 23, 2020. The resulting extreme changes in human behavior may have influenced the air pollutants concentration. However, despite these changes, hazy weather persisted in Shanghai and became a public issue. This study aims to investigate air pollutant mass concentration changes during the lockdown in Shanghai. Air pollutant mass concentration data and meteorological data during the pre-lockdown period and the level I response lockdown period were analyzed by statistical analysis and a Lagrangian particle diffusion model. The data was classified in three periods: P1 (pre-lockdown: 10 days before the Spring Festival), P2 (the first 10 days after lockdown: during the Spring Festival celebration), and P3 (the second 10 days after lockdown: after the Spring Festival). Data for the same period in 2019 were used as a reference. The results indicate that the Spring Festival holiday in 2019 resulted in a reduction in energy consumption, which led to a decrease in PM_{2.5} (26.4%) and NO₂ (43.41%) mass concentration, but an increase in ozone mass concentration (31.39%) in P2 compared with P1. The integrated effect of the Spring Festival holiday and lockdown in 2020 resulted in a decrease in PM_{2.5} (36.5%) and NO₂ (51.9%) mass concentrations, but an increase in ozone mass concentration (43.8%) in P2 compared with P1. After the Spring Festival, the mass concentrations of PM_{2.5}, SO₂, and NO₂ increased by 74.41%, 5.52%, and 53.28%, respectively in P3 compared with P2 in 2019. However, PM_{2.5} and SO₂ concentrations in 2020 continued to decrease, by 14.74% and 4.61%, respectively, while NO₂ mass concentration increased by 7.82% in P3 compared with P2. We also found that PM_{2.5} mass concentration is susceptible to regional transmission from the surrounding cities. PM_{2.5} and other gaseous pollutants show different correlations in different periods, while NO₂ and O₃ always show a strong negative correlation. The principal components before the Spring Festival in 2019 were O₃ and NO₂, and after the Spring Festival, they were PM_{2.5} and CO, while the principal components before the lockdown in 2020 were PM_{2.5} and CO, and during lockdown they were O₃ and NO₂.

Keywords COVID-19 · Air-pollutant mass concentration · Lagrangian particle dispersion model · Spring festival · Shanghai

Introduction

Urban air quality can be improved by controlling anthropogenic emissions. China has a lot of successful examples, such

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as during the 2008 Beijing Olympic Games, the 2010 Shanghai world expo, the 2014 Asia-Pacific Economic Cooperation (APEC) meeting, and other major events and exhibitions. The Chinese government has adopted a series of controls (to temporarily reduce anthropogenic emissions from factories, industrial plants, construction sites, vehicles, and gas stations) to ensure a good atmospheric environment in the host cities (Ma et al. 2010; Huang et al. 2013, 2015).

As an extreme event, to mitigate the possible impacts due to the outbreak of COVID-19, a series of lockdown activities have been implemented in many countries. The impact of these policies on the atmospheric environment has attracted the attention of scholars worldwide and provided special opportunities for atmospheric researches (Nakada and Urban 2020; Bashir et al. 2020; Kraemer et al. 2020; Tobias et al. 2020). Several studies have shown that these counter-COVID-19 measures have played a significant role in improving air

quality (Chauhan and Singh 2020; Collivignarelli et al. 2020; Fuwape et al. 2020; Isaifan 2020; Kerimray et al. 2020; Li et al. 2020; Otmani et al. 2020; Shakoor et al. 2020).

China was the first country to carry out national lockdown policies to restrict travel, shut down commercial activities, and require its people to stay at home, beginning in late January 2020 (Tian et al. 2020; Wang et al. 2020a). Satellite imageries from the European Space Agency (ESA 2020) and the National Aeronautics and Space Administration (NASA 2020) have shown that the volume of NO₂ over China decreased significantly due to a decline in economic activity and energy consumption resulting from the COVID-19 lockdown. However, Wang et al. (2020b) point out the fact that a severe haze still occurred in the North China Plain during the lockdown. The significant reductions in traffic emissions and small reductions in industrial emissions could not help to reduce the severe air pollution in China, especially in unfavorable meteorological conditions. In addition, the secondary aerosols were the main cause of severe haze pollution in winter in eastern China (Wang et al. 2020c). Wang et al. (2020b) find the background and residual pollutions are still high during lockdown over the Yangtze River Delta Region.

Since the start time of lockdown overlaps with the Spring Festival in China this year, so the air pollutant changes during lockdown are actually influenced by the combination of the Spring Festival and the epidemic prevention and control. However, most of these existing studies mainly focus on the changes of air pollutants before and after lockdown, and few compared the differences of air pollutants before and after the Spring Festival in previous years and 2020. Therefore, in order to better illustrate the changes of air pollutants during these periods, Shanghai which is the most populous urban area in China and the second-most populous city proper in the world is chosen as the target area. It suffered from PM_{2.5} concentration during the lockdown period, which became a public issue.

First, we divided the research time into three periods according to the start time of lockdown and the Spring Festival (see “The Research Period Determination” chapter for details). Secondly, statistical and a Lagrangian particle diffusion model (LPDM) are conducted to comprehensively analyze the characteristics of air pollutant concentration, meteorological conditions, and influencing factors in 2019 and 2020. The results can provide basic data for the prevention and control of urban air pollution.

Background

The daily confirmed cases of COVID-19 from January 20 to February 12 in 2020 in Shanghai were summarized in Fig. 1. The number of confirmed cases per day increased rapidly from January 20 to 30. The number of reported COVID-19 cases in Shanghai reached its maximum, with about 27 new cases on

January 30. This may be related to the Chinese Spring Festival. The spread of COVID-19 is accelerated to a certain extent by the mass migration due to the celebration of the Spring Festival. Quarantine measures were effective in curbing the spread of the virus, and the number of confirmed cases per day dropped significantly from January 31 to February 12.

As shown in Fig. 2, before the Spring Festival holiday, some enterprise and supermarket stores remained open until January 23 while universities and school activities continued until January 20 and 18 in 2020. With the rapid spread of infections, the government adopted strong containment measures in Shanghai: only factories producing essential supplies (e.g., food, epidemic prevention materials) were authorized to remain operative. The Spring Festival in 2020 has been extended from the original 7 days (January 24–January 30) to 10 days (January 24–February 2) when the partial lockdown was declared. Even on February 2, many cities still strictly controlled population movement and resumption of work and production. The Spring Festival holiday in 2020 was extended resulting in a much lower population flow than during the Spring Festival in 2019. It was not until March 24 that the epidemic prevention and control was adjusted to the second-level response, and social activities gradually resumed.

This has had a negative impact on the economy. As illustrated in Fig. 3, Shanghai’s GDP in the first quarter was 7856.62 billion yuan: a year-on-year decrease of 5.44%.

Materials and methods

Data collection

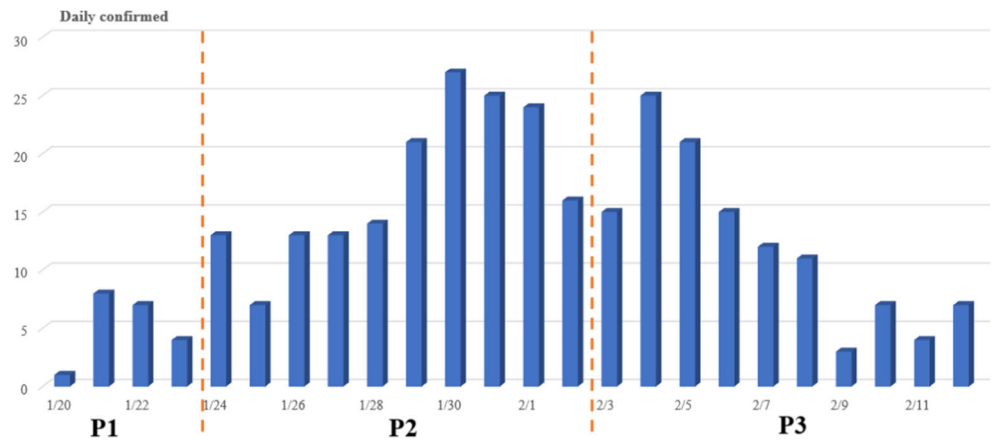
This study uses the real-time air pollutant (SO₂, NO₂, CO, O₃, PM_{2.5}) hourly mass concentration of the Yangpu sipiao monitoring station released by the Shanghai Municipal Ecological Environment Bureau (<https://sthj.sh.gov.cn/>) data. The air monitoring location is indicated by the red point in Fig. 4. The meteorological parameters, including atmospheric pressure, wind direction, wind speed, air temperature, relative humidity, and rainfall, were measured by the AG1000 automatic weather station at the point shown in blue in Fig. 4. The instruments were set up on tall-building roofs, approximately 90 m above ground level. The distance between the air quality monitoring stations and meteorological stations is 3 km.

Data processing

Research period determination

On January 24, 2020 (Spring Festival’s Eve), Shanghai carried out lockdown policies. The lockdown coincided with the Spring Festival holiday, when normal production activities usually decline. In order to understand the details of the air

Fig. 1 Daily Changes in new confirmed cases of COVID-19 in Shanghai. Source: (Shanghai Municipal Health Commission,2020)



pollutant mass concentration changes, we considered the integrated effect of the lockdown policy and the Spring Festival. The data was classified in three periods in 2020: P1, January 14–23 (pre-lockdown: before the Spring Festival), P2, January 24–February 2 (the first 10 days after lockdown: during the Spring Festival celebration) and P3, February 3–12 (the second 10 days after lockdown: after the Spring Festival holiday), and data for the same period in 2019 were used for comparative analysis.

Statistical analysis

A Spearman correlation test (Hauke and Kossowski 2011) between the air pollutant mass concentration and meteorological elements and principal component analysis (PCA) (Abdi and Williams 2010) of the air pollutant mass concentration during the observation period were carried out using SPSS 19.0 software.

Lagrangian particle dispersion modeling

The backward Lagrangian particle dispersion model (LPDM) based on HYSPLIT (Stein et al. 2015) was adopted to analyze

the transport and dispersion processes of tracer gases. Ten thousand particles were released at a selected location of 100 m and traced backward each hour for 72 h during the study period. After the particles were released from the receptor point, their positions were calculated by considering the mean wind field and turbulent transport in the planetary boundary layer (Ding et al. 2013). The contribution from potential source regions is explained by the footprint retro-plume which expresses the residence time of particles below the 100 m level. (Wang et al. 2020c).

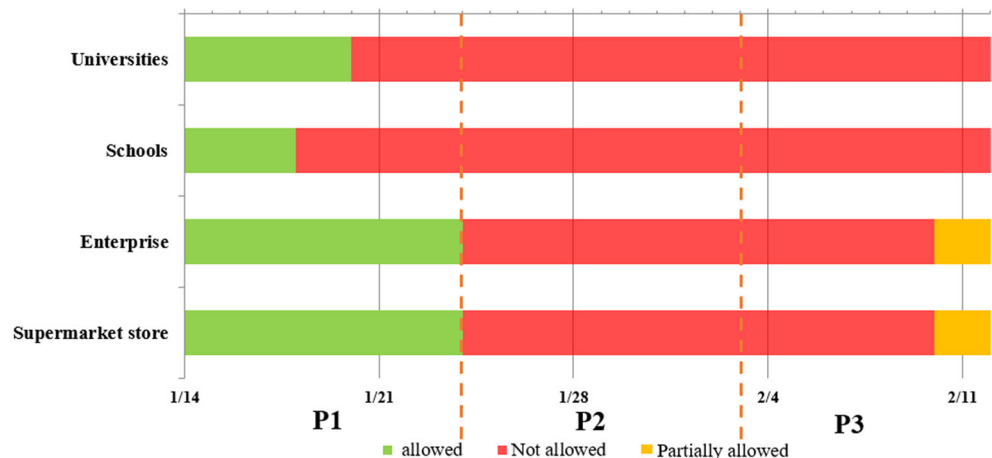
Results and discussion

Meteorological data

Meteorological elements of 2019 and 2020

Figs. S1 and S2 show the time series of meteorological elements in 2019 and 2020, respectively. The temperature suddenly decreased during the Spring Festival in 2019, while there was more rainfall and greater relative humidity in the 2 days before and after the 2020 Spring Festival. Atmospheric

Fig. 2 Scheme of activities allowed and prohibited from January 14 to February 12, 2020 in Shanghai



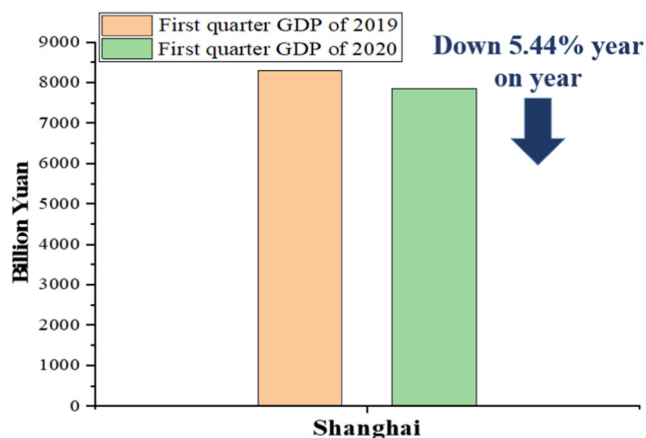


Fig. 3 Statistics of Shanghai GDP in first quarters of 2019 and 2020

pressures were lower during both P2 periods of 2019 and 2020. We compare the meteorological data over different periods in 2019 and 2020. The results are depicted in Table 1.

Figure 5 shows wind rose plots for three periods in 2019 and 2020 in Shanghai. In 2019, during P1 (Fig. 5d), north and west-northwest were the predominant wind directions with average wind speeds of 5 m s^{-1} and 4.3 m s^{-1} . During P2 (Fig. 5e) and P3 (Fig. 5f) of 2019, the wind pattern was similar. Predominant wind directions were northeast and north-northeast during P2 and P3, and the average wind speeds were 4.1 m s^{-1} , 3.7 m s^{-1} and 3.0 m s^{-1} , 3.4 m s^{-1} , respectively. However, in 2020, during P1 (Fig. 5a), the predominant wind directions were northwest and east-northeast, and the average wind speeds were 3.3 m s^{-1} and 3.6 m s^{-1} , respectively. During P2 (Fig. 5b), the predominant wind directions were northwest and west-northwest, and the average wind speeds were 5.8 m s^{-1} and 5.5 m s^{-1} , respectively. During P3 (Fig. 5c), the predominant wind directions were east-

northeast and east, and the average wind speeds were 3.4 m s^{-1} and 3.6 m s^{-1} , respectively.

Air-pollutant mass concentration data

Comparative analysis of 2019 and 2020

Hourly average mass concentrations of O_3 , $\text{PM}_{2.5}$, SO_2 , and NO_2 during P1, P2, and P3 of 2019 and 2020 are plotted in Fig. 6. The boxplots show the distance between the first and third quartiles. The whiskers are set as the extreme data points (lower and upper) not exceeding 1.5 times the quartile range from the median. Different colored curves represent the normal distributions of the data. The average mass concentrations of criteria pollutants and the variations during P1, P2, and P3 of 2019 and 2020 are shown in Table 2. In most cases, the Chinese Spring Festival holiday results in a brief reduction in energy consumption (Ghosh 2020). During the Spring Festival holiday (P2), the mass concentrations of $\text{PM}_{2.5}$, CO, SO_2 , and NO_2 in 2019 decreased by 26.40%, 4.23%, 11.09%, and 43.41%, while O_3 increased by 31.39%. The mass concentrations of $\text{PM}_{2.5}$, CO, and NO_2 in 2020 decreased by 36.5%, 8.6%, and 51.9%, while those of O_3 and SO_2 increased by 43.8% and 0.9%.

Energy consumption will rise again with the resumption of production after the holiday, and the air quality improvement discussed above will not continue (Wang and Su 2020). After the Spring Festival holiday (P3) of 2019, the mass concentrations of $\text{PM}_{2.5}$, SO_2 , and NO_2 in 2019 increased by 74.41%, 5.52%, and 53.28%, respectively, while those of O_3 and CO decreased by 5.18% and 0.80%, respectively. This seems to be an exception because of the large-scale outbreak of COVID-19 in 2020. The Chinese government adopted strict



Fig. 4 Map of Metropolitan area of Shanghai and location of sampling sites

Table 1 Statistical analysis of temperature (T), relative humidity (RH), wind speed (WS), atmospheric pressure (AP), and rainfall (RF) over different periods in 2019 and 2020

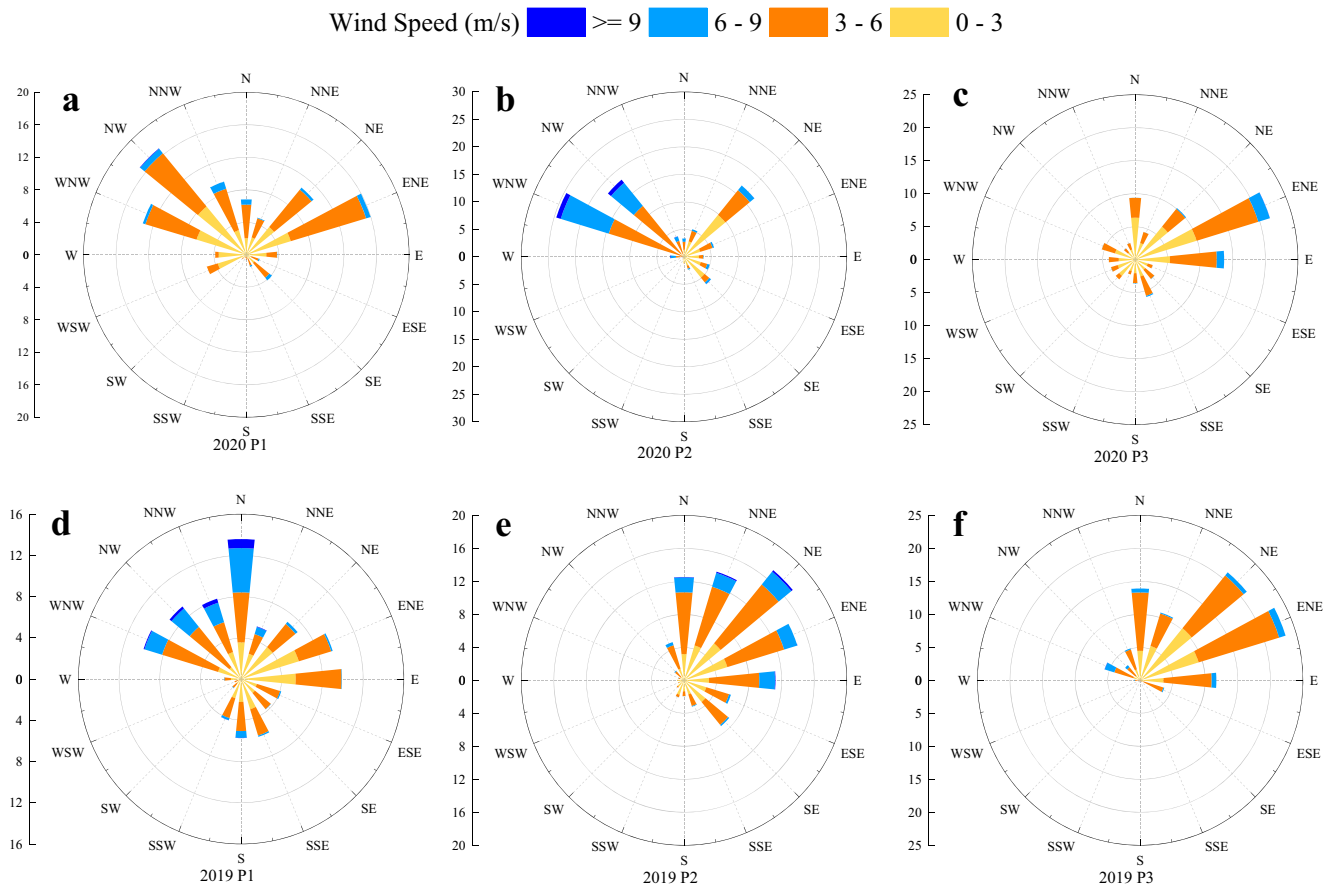
	2019			2020		
	P1	P2	P3	P1	P2	P3
T/(°C)	6.4 ± 3.3	5.3 ± 3.6	4.6 ± 1.4	6.3 ± 2.1	6.2 ± 2.0	7.7 ± 2.6
RH/(%)	72.7 ± 11.6	77.4 ± 10.8	82.8 ± 12.3	78.9 ± 14.2	76.1 ± 19.9	78.1 ± 14.9
AP/(hPa)	1024.1 ± 5.5	1024.9 ± 6.0	1024.3 ± 3.5	1025.5 ± 2.3	1024.7 ± 3.2	1027.5 ± 4.2
WS/(m/s)	3.8 ± 2.0	3.7 ± 1.7	3.6 ± 1.5	3.3 ± 1.5	4.3 ± 2.1	3 ± 1.4
RF/(mm)	6.7	27.7	35.6	65.7	27.1	25.4

restrictions and extended the Spring Festival holiday, leading to a suspension of some production and human activities. As shown in Fig. 3, Shanghai's GDP fell by 5.44% year-on-year in the first quarter.

As can be seen from Figure S3, during P3 of 2020, the mass concentrations of PM_{2.5}, O₃, CO, and SO₂ in 2020 continued to decrease by 14.74%, 0.50%, 0.41%, and 4.61%, respectively, while that of NO₂ increased by 7.82%. NO₂ mass concentration suddenly increased on February 8 (the penultimate day of the Spring Festival holiday), which is related to combustion

of oil, coal, natural gas, and other fuels and exhausts of urban vehicles (Wang and Su 2020).

PM_{2.5} mass concentration during different winds during three periods in 2019 and 2020 are compared in Fig. 7. During most periods, the PM_{2.5} mass concentration was higher during west and northwest winds and lower during east winds. Combined with the conclusions obtained in Fig. 5, during P1, P2 of 2019 and P3 in 2020, the PM_{2.5} mass concentration during the dominant wind was higher than those during other winds. During P3 of 2019 and P2 and P3 in

**Fig. 5** Rose chart of wind speed and direction at different periods of 2019 and 2020

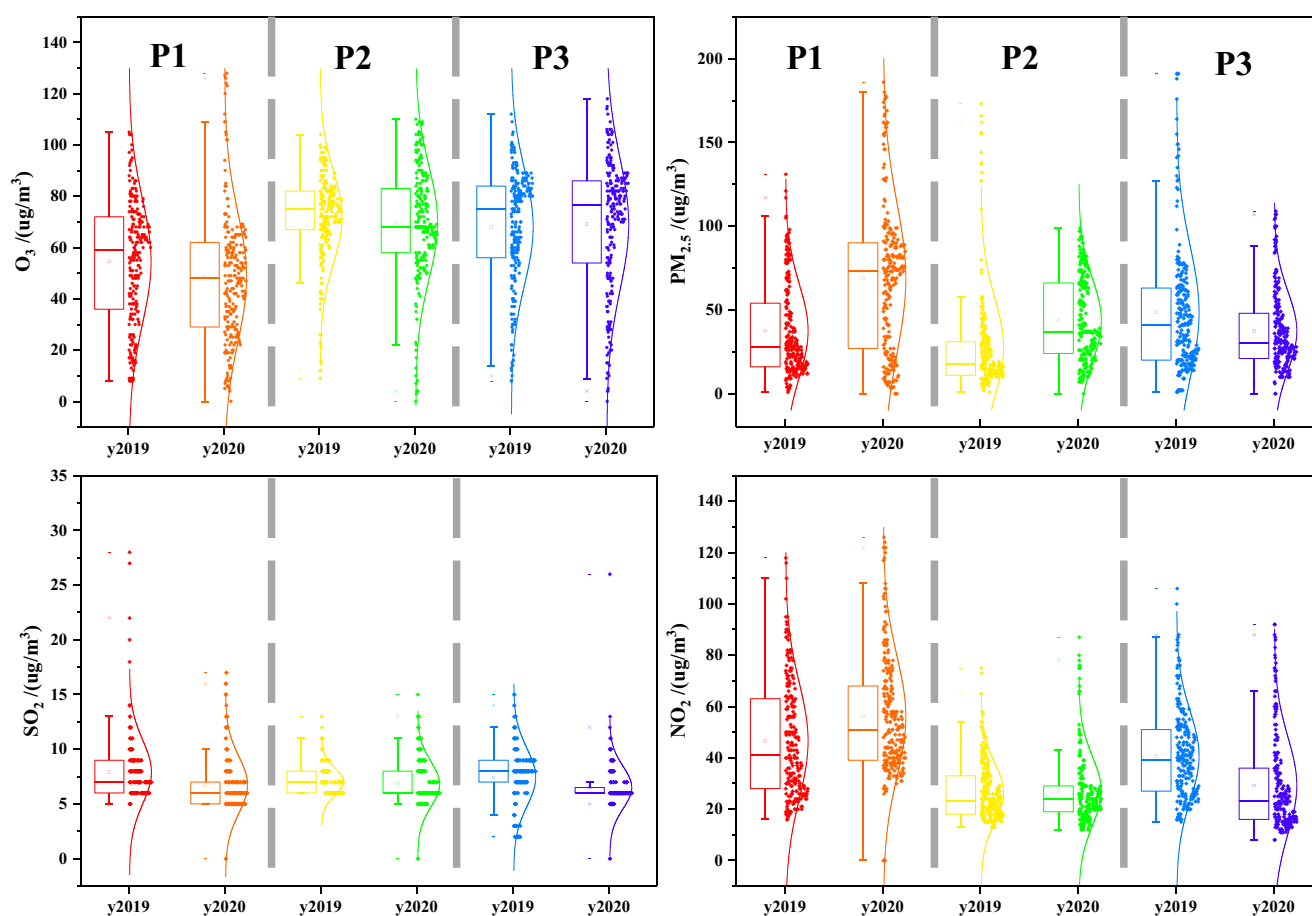


Fig. 6 Hourly average concentration of O_3 , $PM_{2.5}$, SO_2 , and NO_2 during P1, P2, and P3 periods of 2019 and 2020

2020, the $PM_{2.5}$ mass concentration during the dominant wind was lower than those during other winds.

Lagrangian particle dispersion model

With reduced activities, hazy weather still occurred in Shanghai, becoming a public issue. The LPDM model was

Table 2 Average concentrations of air pollutants during different periods in 2019 and 2020 $\mu\text{g}/\text{m}^3$ (except for $\text{CO}:\text{mg}/\text{m}^3$)

		$PM_{2.5}$	O_3	CO	SO_2	NO_2
2019	P1	37.56	54.63	1.09	7.92	46.61
	P2	27.65	71.77	1.04	7.05	26.38
	P3	48.22	68.06	1.03	7.44	40.43
	P2-variation/%	-26.40	31.39	-4.23	-11.09	-43.41
	P3-variation/%	28.37	24.59	-5.00	-6.18	-13.25
2020	P1	68.8	48.4	1.1	6.7	56.1
	P2	43.7	69.6	1.0	6.8	27.0
	P3	37.3	69.3	1.0	6.5	29.1
	P2-variation/%	-36.5	43.8	-8.6	0.9	-51.9
	P3-variation/%	-45.8	43.1	-9.0	-3.7	-48.1

carried out to determine the source of pollutant particles and investigate their transport routes. During the observation period, we calculated the retro-plumes based on 3-day (72 h) backward Lagrangian particle dispersion modeling of every hour, and then took the daily average of the trajectory obtained during the 24 h.

According to Chinese ambient air quality standards (GB 3095-2012), the 24-h average secondary concentration limit for $PM_{2.5}$ is $75 \mu\text{g}/\text{m}^3$, beyond which it is considered excessive. Therefore, the simulation results of 5 days exceeding $75 \mu\text{g}/\text{m}^3$ were selected in Fig. 8, and the day with the lowest $PM_{2.5}$ mass concentration ($8.0 \mu\text{g}/\text{m}^3$) was also selected as the representative of the clean day as the reference. During the observation periods, the pollution air masses reaching Shanghai mainly came from the urban agglomeration around Shanghai, in which the Yangtze River Delta region made a significant contribution. Air pollutants from Shandong, Henan, and other regions over a long-range transport and secondary pollutants produced by further oxidation during transmission will also be transported to Shanghai. Figure 8a suggests that the air masses arriving at Shanghai were mainly from central and northern Jiangsu Province and were short-term air

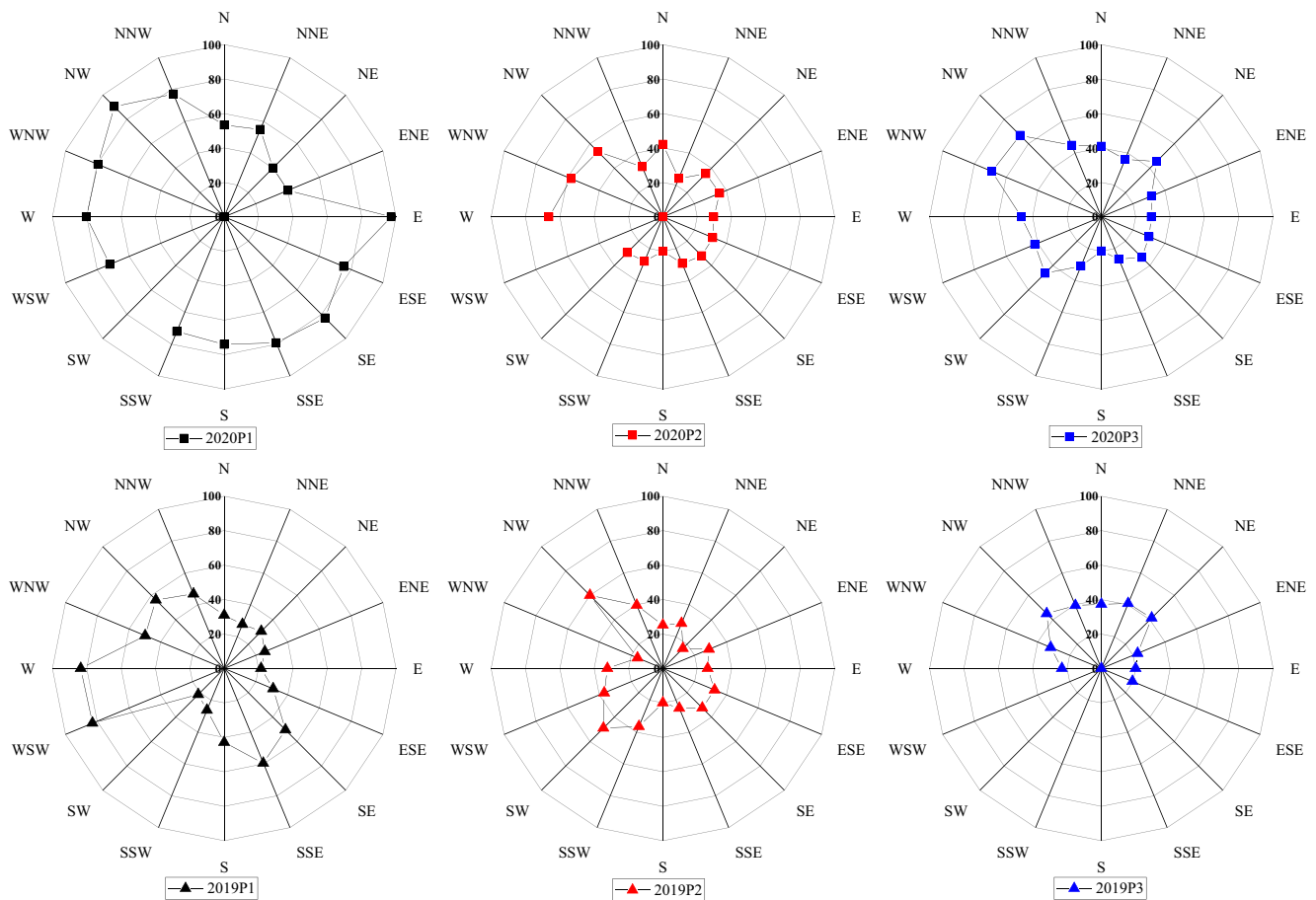


Fig. 7 Distribution map of $PM_{2.5}$ mass concentration under different wind directions in different periods of 2019 and 2020

masses, reflecting that the source emission and accumulation of local pollutants contributed to the mass concentration of particles in Shanghai. On January 20 (Fig. 8d), the daily average mass particle concentration in Shanghai reached the highest peak value over all the observation periods, the $PM_{2.5}$ mass concentration being $132.7 \mu\text{g}/\text{m}^3$. During this time, the particles in the surface layer of the cities around the Yangtze River Delta were transported to Shanghai and accumulated over the Shanghai area. On January 16 (Fig. 8b), $PM_{2.5}$ mass concentration was the lowest, being mainly affected by the dilution of clean air masses from the ocean. Cloud maps of $PM_{2.5}$ monitoring data across the country (taking January 20 and 28 as examples) also confirm the Lagrangian simulation results.

Correlation analysis of air pollutants mass concentration in 2020

Table 3 presents the Spearman correlation coefficients between air pollutants mass concentration and meteorological elements. Air pollutants mass concentration show significant correlations with each other, meteorological elements show a negative

correlation with $PM_{2.5}$ except for air pressure, and all of them show correlation with O_3 , while they show no correlation with CO, and relative humidity shows a negative correlation with SO_2 and wind speed shows negative correlation with NO_2 .

Table S1 presents the Spearman correlation coefficients between mass concentrations during P1 of 2020. $PM_{2.5}$ shows a strong positive correlation with SO_2 and NO_2 : 0.661 and 0.666, respectively. This indicates that on the one hand, SO_2 , NO_2 , and $PM_{2.5}$ have certain homology; on the other hand, SO_2 and NO_2 can generate secondary particles after complex chemical reactions occur in the atmosphere. SO_2 in the atmosphere mainly results from combustion of fossil fuels contaminated with sulfur compounds. Industry, power, and transportation emissions are the main sources of NO_x . Therefore, during P1, it is mainly related to energy consumption. At the same time, O_3 and NO_2 are significantly negatively correlated, with a value of -0.616 . Tables S2-3 show that $PM_{2.5}$ shows weak positive correlation with CO, SO_2 , and NO_2 , because the Spring Festival holiday and lockdown resulted in short-term reduction in energy consumption. O_3 and NO_2 showed negative correlation during these periods.

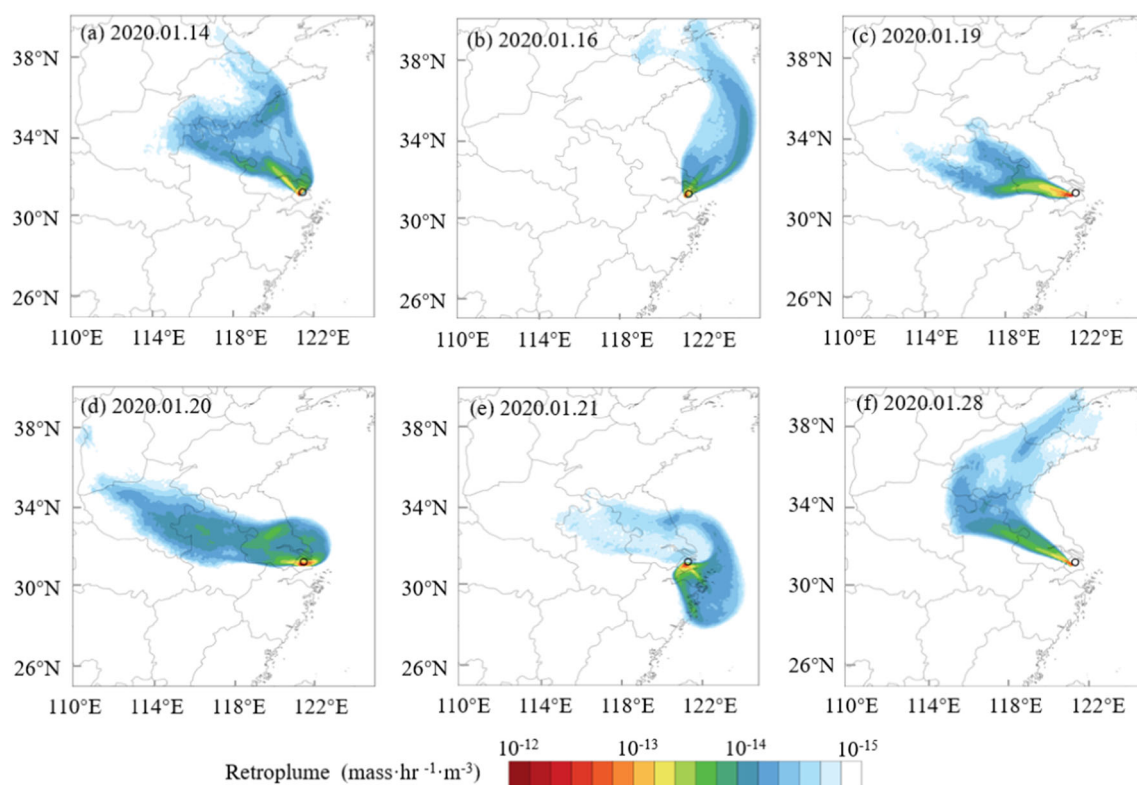


Fig. 8 Results of Lagrangian particle dispersion model

Principal component analysis of air pollutant mass concentration

Tables 4, 5, and 6 show the main results of the PCA application for air pollutants concentration during P1, P2, and P3 of 2020, respectively. For each period, two PCs were selected, which explained 81.26%, 61.62%, and 69.43% of the original data variance, respectively. The rotated factor loadings represent the impact of each variable on the PCs (Pires et al. 2009). According to the absolute load value > 0.75 , $0.75-0.5$, and $0.5-0.3$, Liu et al. (2003) divided the influence of the original variable on each PC into three grades: strong, medium, and

weak. During P1, the first PC (PC1) described in Table 4 made important contributions to $PM_{2.5}$, NO_2 , SO_2 , and CO. PC2 was heavily loaded by the contributions of O_3 . It indicates that the pollution in the P1 period mainly comes from vehicle emissions and industrial emissions. Table 5 shows the main results for P2 of 2020. PC1 made important contributions to O_3 and NO_2 ; PC2 was loaded by the contributions of $PM_{2.5}$ and CO, which indicate that the industrial emissions are no longer the main source of air pollutants due to controls. Table 6 shows that, during P3 of 2020, PC1 made important contributions to O_3 and NO_2 while PC2 was heavily loaded by the contributions of CO and SO_2 . This is because Shanghai

Table 3 Spearman correlation coefficients between air pollutants and meteorological elements of 2020

	$PM_{2.5}$	O_3	CO	SO_2	NO_2	RH	T	WS	AP
$PM_{2.5}$	1								
O_3	-0.254**	1							
CO	0.412**	-0.110**	1						
SO_2	0.458**	0.168**	0.260**	1					
NO_2	0.441**	-0.708**	0.258**	0.115**	1				
RH	-0.276**	-0.215**	-0.055	-0.684**	-0.028	1			
T	-0.164**	0.357**	0.070	0.061	-0.024	0.143**	1		
WS	-0.129**	0.349**	-0.057	-0.058	-0.475**	0.01	-0.197**	1	
AP	-0.039	0.120**	-0.057	0.049	-0.071	-0.184**	-0.199**	-0.243**	1

**Signifies shows significance at 1%

Table 4 Pollutants rotation component matrix (2020P1)

	PC1	PC2
PM _{2.5}	0.931	0.095
CO	0.770	0.175
NO ₂	0.734	-0.559
SO ₂	0.718	0.546
O ₃	-0.223	0.922
Eigenvalue	2.403	1.660
The proportion of variance explained/%	48.06	33.20

gradually started resumption of work and production of its enterprises after the Spring Festival.

Tables S4-S6 show the main results of the analysis of the principal components of air pollution during P1, P2, and P3 in 2019 respectively. The principal components during P1 in 2019 were O₃ and NO₂, and during P3 were PM_{2.5} and CO. The temperature was relatively high and more conducive to the formation of secondary pollutants in photochemical reactions during P1. Thus, the primary pollutant was Ozone. After the Spring Festival, the temperature drops and industrial emissions increase in P3.

Conclusions

This study investigated the air pollutant concentration changes during the Spring Festival and COVID-19 lockdown in Shanghai using both air-pollutant concentration, meteorological monitoring data statistical analysis, and Lagrangian particle diffusion model simulation. We found that P2 (during the Spring Festival) showed a similar trend of atmospheric pollutant concentration in 2019 and 2020 compared with P1 (before the Spring Festival): decrease in PM_{2.5} and NO₂ mass concentrations, but an increase in O₃ mass concentration. However, compared with P3 (after the Spring Festival) and P2, the variation trend of atmospheric pollutant mass concentrations in 2 years are different: the mass concentrations of PM_{2.5}, SO₂,

Table 5 Pollutants rotation component matrix (2020P2)

	PC1	PC2
O ₃	0.913	-0.051
NO ₂	-0.851	0.017
PM _{2.5}	0.001	0.785
CO	-0.138	0.685
SO ₂	0.402	0.505
Eigenvalue	1.739	1.343
The proportion of variance explained/%	34.77	26.85

Table 6 Pollutants rotation component matrix (2020P3)

	PC1	PC2
O ₃	-0.950	0.103
NO ₂	0.912	0.200
CO	0.117	0.769
SO ₂	-0.230	0.735
PM _{2.5}	0.359	0.599
Eigenvalue	1.931	1.540
The proportion of variance explained/%	38.62	30.81

and NO₂ increased in 2019 while PM_{2.5}, O₃, CO, and SO₂ in 2020 continued to decrease. The difference is mainly due to lockdown measures in 2020. We also found that the haze weather in Shanghai during the whole observation period was mainly due to the influence of external transmission, especially the northern areas. The results of correlation and principal component analysis show the changes of atmospheric pollutant concentration characteristics before and after the Spring Festival and epidemic prevention and control. As a conclusion, we think in spite of the dual influence of the Spring Festival and lockdown of COVID-19, the haze also appeared, PM_{2.5} decreases but O₃ rises, posing a challenge to the prevention and control of air pollution in the future: the adjustment of energy structure, the coordinated reduction of air pollutants, and the joint prevention and control among regions.

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