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Important role of turbulent wind gust and its coherent structure in the rapid removal of urban air pollution

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Abstract

The removal process of urban air pollution is very rapid even under the strong obstruction of various buildings in the city. In this study, based on high-accuracy ultrasonic anemometer observations at seven different altitudes on a 325 m tower, we proposed a physical mechanism in which turbulent wind gust and its coherent structure may play important roles in this phenomenon. Pollutants suspended within the urban canopy layer UCL cannot be quickly removed by means of basic flow but diffuse and cross the UCL by means of the coherent structure of gust wind and then propagate further under strong basic flows above the UCL. With a continuous increase in wind speed in the whole layer, combined with gust–wind and turbulence mixing, the rapid transformation from heavily polluted days to clean days in urban areas can take place in just a few hours. Turbulent wind gust and its coherent structure were extracted by third-order Daubechies wavelet transformation. The downwind wind was decomposed into three separate components, basic flow $\bar{u}(t)$, gust–wind $u'_g(t)$, and turbulence $u'_t(t)$. The results show that in the early rapid drop of urban surface pollutant concentration, horizontal wind speed at 8 m was still low, and sinking movements dominated in the lower layer. Friction velocity calculated from gust–wind $u_w$ significantly affected the surface PM$_{2.5}$ concentration, and was the most obvious factor with an inverse correlation coefficient $-0.56$. The correlation coefficient of coherent structure of gustiness $R_{u_gu_g}$ at 8 m basically changed to positive values before the rapid decline of the surface PM$_{2.5}$ concentration. The concentration of PM$_{2.5}$ decreased significantly when $R_{u_gu_g} > 0$, and exhibited an increasing trend when $R_{u_gu_g} < 0$. The close relationship between the concentration of PM$_{2.5}$ and $R_{u_gu_g}$ indicated the important role of the coherent structure of gustiness in the rapid removal process of urban pollutants. The research deepens the vertical exchange process of matter and energy in the UCL, and provides a scientific reference for the rapid dissipation mechanism of urban air pollution.

1. Introduction

The atmospheric boundary layer (ABL) is located at the bottom of the troposphere, generally approximately 1–2 km away from the ground, and is the main place for human production, life and industrial activities (Stull 1988). The exchange of material and energy between the surface and the free atmosphere through ABL has significant influences on weather, climate (Steinberger and Ganor 1980, Dawson et al 2007), and air pollution (Salmond and Mckendry 2005, Xu et al 2006, Quan et al 2021). With the rapid development of urbanization and industrialization, a large number of pollutants have been discharged into the atmosphere, especially for large-scale cities where there are often denser populations and road networks (Guo et al 2016, Li et al 2020). Under unfavorable conditions, such as low winds, strong inversion layers and high humidity, pollutants emitted into the atmosphere could grow rapidly (Pan et al 2009, Lyu et al 2018, Shi et al 2019, Xiang et al 2020), often causing serious air pollution events (Weber et al 2007).
Many cities in China have experienced rapid urbanization and economic development over the past decade, accompanied by increased anthropogenic emissions and pollutants, leading to heavy air pollution (Liu et al. 2019, Li et al. 2020, Wang et al. 2020). China has synchronously monitored the concentrations of six main air pollutants, namely PM$_{2.5}$ (particles with aerodynamic diameter less than or equal to 2.5 μm), PM$_{10}$, SO$_2$, NO$_2$, O$_3$, and CO at environmental monitoring stations over the country, and among them, particulate matter is the most primary air pollutant. Since most of the pollution sources are distributed near the ground, in most cases, such as when there are no obvious elevated pollution sources or regional transportation of pollutants, previous vertical profiles of particles observed show that the concentration of particulate matter near the ground was highest (Lyu et al. 2018, Sun et al. 2021). The surface PM$_{2.5}$ during heavy pollution in Beijing often experiences slow accumulation for about 3–4 days (Wu et al. 2017), and then under strong winds, its concentration decreases rapidly within a few hours, showing obvious ‘ramp-like’ structures (Shi and Hu 2020).

Compared with the slow accumulation of PM$_{2.5}$, its removal process is very rapid despite the great blocking effects of various buildings in the city. However, the wind speed near the ground in the ABL is always relatively small compared with that in the upper layer. The existence of various buildings within the urban canopy layer (UCL) further significantly attenuates the wind speed near the ground (Wang et al. 2020). In addition, due to the obstruction of the UCL, even if the wind speed is high near the ground, it cannot directly and quickly blow away the pollutants in the UCL. The simulation results show that the maximum wind speed in the UCL was reduced by about 1 m s$^{-1}$, and the maximum vertical turbulence diffusion coefficient increased by 60–70 m$^2$ s$^{-1}$ (Huszar et al. 2018) after the urban canopy forcing was considered. However, the physical mechanism of rapid removal of air pollutants in the UCL within a few hours has been less studied and is still lacking.

The diffusion and transport of pollutants in the atmosphere are inseparable from the atmospheric turbulence vortex structures. The flow in the ABL has a turbulence character (Stull 1988, Liu et al. 2020), and turbulence is an essential part of the mechanism that disperses air pollutants resulting from anthropogenic activities (Sorbian 1989). Atmospheric turbulence consists of many vortex structures of different scales (Hu 1998). Large-scale coherent vortices can carry the most kinetic energy, while small-scale vortices are mainly involved in diffusion and energy dissipation processes. The typical constitutive motions of coherent structures make the greatest contributions to the enhancement of transport processes of various pollutants, heat or momentum (Ferrer et al. 2013). However, previous studies have paid less attention to the role of different turbulence vortices and its coherence structure in the removal of urban air pollutants. The study of this phenomenon relies on high-accuracy urban vertical gradient measurements of turbulence, because the diffusion and transmission of air pollutants in the atmosphere are mainly controlled by turbulence activities, especially in the small wind stagnant synoptic systems.

In fact, Zeng et al. (2007, 2010) found that turbulence gustiness is an important mechanism of sand dust emissions near the ground, and proposed that owing to the 3-dimensional coherent structure of gust wind, dust particles can effectively overcome systematic descending air motions and penetrate from the bottom levels into the ABL. Dust particles then propagate into and diffuse in the upper levels of the ABL and troposphere, where ascending air motion prevails. The ascending motion of dust particles must rely on coherent structures or obviously complete vortex structures, but turbulence and small-scale convection in the ABL lack coherent structures. Cheng et al. (2012) explained the mechanism of soil erosion and sand entrainment by the coherent structure of wind gusts by means of Lattice Boltzmann Method. The implementation of the gust-wind model could help improve the simulation performance in the concentration of PM$_{10}$ during severe sand and dust storms (Wang et al. 2022). Models for dust storm forecasting could be improved by utilizing atmospheric humidity and wind speed as the main drivers for dust generation and transport (Csavina et al. 2014). All the above studies have shown the important role of gusts in the generation and transport of sand dust.

During haze pollution days, haze particles, such as PM$_{2.5}$, are smaller than dust particles, and haze particles should theoretically also be more easily carried and transported to high levels by gust–wind. Gust–wind, generally speaking, refers to the strong turbulence wind speed fluctuations in the ABL. Its duration is relatively short, usually for seconds to minutes (Li et al. 2016). Observation results show that gustiness often leads to sharp changes in temperature and humidity (Acevedo et al. 2016), and their coherent structures often lead to drastic changes in atmospheric scalars such as temperature, relative humidity, and the concentration of CO$_2$ (Foster et al. 2006). The observation results show that gusty disturbances are the strongest fluctuations, contributing about 60% the kinetic energy of eddy kinetic energy under weak mean wind conditions (Li et al. 2016). Based on the above consideration, what effect does gustiness have on the variation in haze particles? In particular, due to the blocking effect of buildings in the UCL, even strong winds cannot directly blow away the pollutants suspended in the UCL. Are haze particles the same as sand dust particles that must be lifted beyond the UCL before they can be quickly blown away by the strong wind?

The Beijing 325 m meteorological tower is located on a typical urban underlying surface surrounded by tall buildings. The tower is equipped with seven layers of three-dimensional ultrasonic anemometers, thus providing a good platform for studying this phenomenon. An in-depth analysis of the turbulence fluctuation
signal of the urban underlying surface is helpful to figure out the physical mechanism of the rapid removal of urban air pollutants in a few hours and to further improve the prediction of air quality for cities.

**Data and methods**

The observation data used in this study were from 7 layers (8, 15, 47, 80, 140, 200, and 280 m) of a three-dimensional ultrasonic anemometer (wind master, gill, UK) and 15 layers (8, 15, 32, 47, 65, 80, 103, 120, 140, 160, 180, 200, 240, 280, and 320 m) of temperature (HC2-S3, Switzerland) and relative humidity (HC2-S3, Switzerland) of 325 m meteorological tower at the Institute of Atmospheric Physics (IAP) of the Chinese Academy of Sciences in Beijing. The sampling frequency of the ultrasonic anemometer is 10 Hz. The average time used in this study was 20 min (Mahrt 2010, Lyu et al 2018). $u$, $v$ and $w$ are the longitudinal, lateral and vertical velocity components, respectively. First coordinate rotation was used on the original data to determine the main wind direction and make $v$ zero. The downwind wind $u$ therefore refers to the horizontal wind. Any data with a bias greater than five standard deviations in the selected time window were marked as a spike. Thresholds are given as Vickers and Mahrt (1997), and the absolute limit for horizontal wind is 30 m s$^{-1}$, and for temperature it is $-30^\circ$C to $50^\circ$C. We used the linear detrending method and discarded the unreliable observations (Kaimal and Finnigan 1994).

The hourly averaged concentration of surface PM$_{2.5}$ at the Olympic Sport Center Station (OSCS), about 2 km from the 325 m tower, was downloaded from the official website of the Beijing Environmental Protection Agency (http://beijingair.sinaapp.com/) (Shi et al 2019). This study focused on the role of gustiness in the rapid removal process of pollutants. The selected case is from 29 November (Nov) to 4 December (Dec) 2017 in Beijing. During this period, the concentration of PM$_{2.5}$ experienced a slow accumulation, approaching 250 $\mu$g m$^{-3}$, and then the pollutants were quickly removed.

The first problem is how to extract gustiness. According to the previous study, it is better to take the third-order Daubechies (DB3) wavelet transformation for 5–9 decompositions for the ABL turbulence signals in Beijing winter (Hu 1998). Therefore, DB3 transformation to a 9-layer decomposition on the original turbulence signals observed by the Beijing 325 m meteorological tower was utilized in this paper. In this way, the original turbulence signal (represented by $S$ in this study) can be decomposed into:

$$S = a9 + d9 + d8 + d7 + d6 + d5 + d4 + d3 + d2 + d1$$  \hspace{1cm} (1)

where 'a' represents 'approximations' and 'd' represents 'details'. The number after 'd' indicates the decomposition layer. The smaller number corresponds to the deeper decomposition layer and the closer details. Therefore, if the 'details' parts of the three velocity component fluctuations are very close on one layer, that is, the difference is very small, it can be considered that the turbulence on that layer is close to isotropic motion, and the signal above that layer is regarded as gust-wind disturbance.

The three velocity component fluctuations $u'$, $v'$ and $w'$ from 29 Nov to 4 Dec 2017 were decomposed by DB3 wavelet transformation, and the fractional dimensions of each layer of $u'$, $v'$ and $w'$ (9 layers in total) were calculated. The 'layers' in figures 1(a), (b) represent the layer with the smallest difference in the fractal dimension of the three velocity component fluctuations, indicating that the turbulence at that layer approaches isotropic motion. $e_v$ and $e_v$ represent the kinetic energy of gust-wind and turbulence fluctuation, respectively. Based on this method, if the layer with the smallest difference in the fractal dimension of three velocity component fluctuations is closer to the first layer (i.e. the smaller number of 'Layers' in figure 1(a)), at this time, $e_v$ is two orders of magnitude smaller than $e_v$. The large vortex plays a leading role, and the turbulence kinetic energy is very small. If the layer with the smallest difference in the fractal dimension of three velocity component fluctuations is close to layer 9 or 8 (i.e. the larger number of 'Layers' in figure 1(a)), although $e_v$ is generally lower than $e_v$, the kinetic energy contributed by the turbulence significantly increases, $e_v$ and $e_v$ are of the same order of magnitude.

The above analysis showed that the combination of DB3 wavelet transformation and fractal dimension can effectively and reasonably extract the gustiness and turbulence in the pulse part. Therefore, $u(t)$ can be expressed as:

$$u(t) = \bar{u}(t) + u'_g(t) + u'_w(t)$$  \hspace{1cm} (2)

where $\bar{u}(t)$, $u'_g(t)$, and $u'_w(t)$ represent basic air flow, gust-wind and turbulence, respectively. For convenience, hereafter we simply denoted $u_g$ and $u_t$ to represent $u'_g(t)$ and $u'_w(t)$ respectively. Figures 1(c) and (d) list the $u$ measured by the three-dimensional ultrasonic anemometer at 280 m and 8 m of the Beijing 325 m meteorological tower from 00:00 to 00:20 on 29 Nov 2017, and the corresponding gust-wind $u_g$ and turbulence wind $u_t$. The minimum difference in fractal dimension used in this paper can effectively extract the gust-wind structure.
Results and discussion

3.1 Time series of the basic air flow

This study focused on a serious haze pollution process in Beijing from 29 Nov to 4 Dec 2017. During this period, Beijing entered the winter heating period, and local emissions such as vehicle emissions and coal combustion were the main source of PM$_{2.5}$ in Beijing. In addition, Beijing was often controlled by the stagnant synoptic system in winter, usually resulting in poor diffusion capacity and accelerating the accumulation of pollutants (Miao et al 2017, Xu et al 2017). Figure 2 shows the time series of the concentration of PM$_{2.5}$, basic air flow (horizontal wind speed $V$ and vertical wind speed $w$), temperature $T$ and relative humidity $RH$ at 8 m, and wind direction at 280 m. Figure 2(b) shows that the $V$ observed at different heights of the tower exhibits obvious low-frequency gustiness, and strong winds lasted about 9 h (such as 01:00–10:00 on 3 Dec). The small winds on 29 Nov had oscillations of about 4 h, possessing continuous gustiness. According to the definition of gustiness by the World Meteorological Organization (WMO), the frequency of gustiness is one to several minutes and this periodic oscillation cannot be clearly distinguished from the basic air flow (Cheng et al 2007).

The concentration of pollutants is closely related to wind speed, and a larger wind speed is obviously not conducive to the accumulation of pollutants (Emeis and Schäfer 2006). During the continuous rise period of the concentration of PM$_{2.5}$ (30 Nov to 2 Dec), the increasing wind speed appeared within the tower, e.g., at 280 m, $V$ exceeded 10 m s$^{-1}$. However, because $V$ at the lower layer was still low, no more than 2 m s$^{-1}$, even if $V$ at the high layer was large, the PM$_{2.5}$ near the ground continued to accumulate. At noon on 30 Nov, $V$ at 140, 200, and 280 m was lower than 5 m s$^{-1}$, but $V$ at 8 m was relatively high on that day, so the concentration of ground PM$_{2.5}$ remained low. It is generally believed that a $V$ at 8 m greater than 3 m s$^{-1}$ is very conducive to the removal of pollutants.
The pollutants accumulated slowly for 3–4 days, and the concentration of surface PM$_{2.5}$ increased slowly, approaching to 250 $\mu$g m$^{-3}$. After 00:00 3 Dec, the concentration of PM$_{2.5}$ decreased sharply and was mainly accompanied by a northerly wind. During the early stage of rapid removal of PM$_{2.5}$ (00:00–03:00 3 Dec), $V$ on the high layer of the tower began to increase, but $V$ at 8 m did not increase. In this period, the basic air flow contributed little to the decrease in the concentration of PM$_{2.5}$.

This study further analyzed the role of vertical velocity. During the continuous accumulation of pollutants, as shown in figure 2(C), the magnitude of $|w|$ (absolute value of $w$) within the tower layer was very small. Both sinking and ascending motions occasionally appeared at the lower layer of the tower, and $|w|$ was approximately 0.1 m s$^{-1}$. From 30 Nov to 2 Dec, due to the stagnant synoptic system, the vertical exchange process in the lower layer of the ABL was inferred to also be relatively weak, which is conducive to the accumulation of pollutants.

The most remarkable feature of $w$ was that during the rapid removal period of pollutants (00:00 to 06:00 3 Dec), $w$ at 8 and 16 m was basically negative, and $w$ at 47 m basically changed around zero. Ascending motions dominated above 80 m, and the updrafts increased significantly during the rapid removal period. This distribution of $w$ enables the pollutants in the upper layer to be removed quickly through both ascending movements and strong horizontal winds.

However, more pollution sources are often distributed within the UCL, especially in the lower layer of the canopy. It is obvious that the pollutants in the lower layer cannot be quickly removed by means of downdrafts. In addition, the obstruction of various buildings in the canopy to the air flow could greatly reduce the efficiency of the diffusion and removal process of pollutants via mean flows. Therefore, basic air flows are not the main driving factor for the rapid removal of pollutants in the UCL. $T$ and $RH$ at 8 m of the tower have obvious diurnal variations (figure 2(d)). During the rapid removal of the pollutants on 4 Dec, both $T$ and $RH$ decreased, revealing that the removal process is mainly affected by dry and cold air.

### 3.2 Time series of the fluctuation quantities

Previous analysis shows that some small declines occurred during the continuous accumulation of pollutants. At this time, basic air flows in the low layer exert little influence on the variation in pollutants. In addition, basic air flows also contribute little in the early few hours of the rapid decline in the concentration of pollutants. Therefore, we further analyzed the relationship between fluctuation quantities and pollutant concentrations and revealed the rapid removal mechanism of pollutants from the UCL. Previous studies have shown that pollutant concentration and friction velocity have an inverse correlation (Shi and Hu 2020). In this paper, by means of
DB3 wavelet transformation, the wind is further decomposed to obtain gust-wind and turbulence, and friction velocities $u_\text{g}$ and $u_\text{t}$ at 8 m are calculated. The calculation formula is as follows (Zeng et al 2010):

$$u_\text{g} = \sqrt{\frac{1}{3} \left( \frac{
abla w}{w} \right)^2 + \left( \frac{w}{w} \right)^2}$$ (3)

$$u_\text{m} = \sqrt{\left( \frac{u}{u} \right)^2 + \left( \frac{v}{v} \right)^2}$$ (4)

$$u_\text{g} = \frac{1}{2} \left[ \left( \frac{u}{u} \right)^2 + \left( \frac{v}{v} \right)^2 \right]$$ (5)

$$u_\text{g} = \frac{1}{2} \left( \frac{u}{u} \right)^2 + \frac{1}{2} \left( \frac{v}{v} \right)^2$$ (6)

$$u_\text{g} = \frac{1}{2} \left( \frac{u}{u} \right)^2 + \frac{1}{2} \left( \frac{v}{v} \right)^2$$ (7)

$u_\text{g}$ and $u_\text{m}$ indicate the friction velocity caused by gust-wind and small-scale turbulent eddies, respectively; $u_\text{g}$ and $u_\text{m}$ indicate the friction velocity calculated by basic air flow and turbulence fluctuations, respectively. $u_\text{tg}$ is the total friction velocity caused by air flows, including not only the basic air flow but also the turbulence activities. As shown in figure 3(b), $u_\text{g}$ and PM$_{2.5}$ concentrations exhibit obvious inverse correlations, even in stagnant weather from 1 Dec to 2 Dec, when there were small decreases in the concentration of PM$_{2.5}$ and basic air flow had little indicative significance of the concentration of PM$_{2.5}$. $u_\text{g}$ had large values in the rapid removal period (3–4 Dec) of pollutants, and the maximum value was more than 0.5 m s$^{-1}$, much higher than $u_\text{m}$. The value of $u_\text{g}$ increased significantly only when $V$ of the whole tower layer increased significantly in the rapid removal period.

It is noteworthy that $u_\text{g}$ also significantly affected the concentration of PM$_{2.5}$ in the continuous accumulation of pollutants during the stagnant synoptic system, and it was the most obvious factor with an inverse correlation coefficient of $-0.56$. $u_\text{g}$ was comparable to $u_\text{g}$ when the concentration of PM$_{2.5}$ was low. $u_\text{g}$ decreased significantly, and its value was lower than $u_\text{g}$ and $u_\text{g}$ when the pollutant concentration was high, indicating that $u_\text{g}$ produced by basic flow is no longer an important influencing factor.

There were obvious diurnal variations in sensible heat flux $\overline{w'\theta'}$, at 8 and 280 m (figure 3(c)); sensible heat flux generally became positive after sunrise in the daytime, reaching a maximum around noon, and then gradually decreased to zero at night. During the rapid removal period of pollutants, $\overline{w'\theta'}$ in both the low and high layers changed negatively. The stratification mainly remained neutral at 8 m, as proven by $z/\Lambda$ near zero, when $V$ was high.

### 3.3 Time series of the fluctuation quantities

We further analyzed the gust-wind at different heights. As shown in figure 4, $|u_\text{g}|$ of these four heights (8, 4, 140, and 280 m) and the concentration of surface PM$_{2.5}$ show obvious inverse correlations. When $|u_\text{g}|$ was large, the
PM$_{2.5}$ concentration was low (such as noon on 30 Nov, 3 Dec and 4 Dec) or showed a declining trend (noon on 1 Dec and 2 Dec). There was no obvious difference in $u_4$ at these four heights, basically changing synchronously, but the value $|u_{280}|$ at 280 m was slightly smaller than that of the other three layers.

The performances of $w_g$ and $u_g$ were not exactly the same. The most obvious difference was that $|w_g|$ on the lower layer of the tower was significantly higher than that on the upper layer, especially the value $|w_g|$ at 47 m, which was larger. This feature was inferred to be mainly caused by strong wind shears at the top of the UCL, because the UCL height around the tower was estimated to be approximately 47 m. Various tall buildings, trees and other obstacles in the canopy have great disturbance to the air flow, and this is an important source of mechanical shear turbulence in the UCL (Kaimal and Finnigan 1994). The $|w_g|$ of 280 m was lower than that of the other three layers, because 280 m is far beyond the UCL. There was a significant negative correlation between $|w_g|$ and the concentration of pollutants in each layer, even when the concentration of PM$_{2.5}$ was low, such as noon on 30 Nov, especially for 8 and 47 m. Considering that $\overline{w}$ at the lower layer of the tower was mainly negative during the rapid removal of the pollutants and horizontal wind was also blocked by various buildings in the UCL, it can be concluded that the rapid removal of pollutants in the lower layer of the UCL was mainly affected by gustiness.

### 3.4 Coherent of gustiness and its correlation with PM$_{2.5}$

We further analyzed the correlation coefficient $R_{u_gw_g}$ of $w_g$ and $u_4$ during the observation period and its relationship with the pollutant concentration. By calculating the correlation coefficient, the coherence degree of gustiness in the corresponding period can be quantitatively reflected. The calculation formula of $R_{u_gw_g}$ is as follows:

$$R_{u_gw_g} = \frac{\overline{u_g w_g}}{\overline{(u_g^2 w_g^2)}}^{1/2}$$  

$R_{u_gw_g}$ at 8 m and the concentration of PM$_{2.5}$ had an obvious inverse correlation, revealing the close relationship between the coherent structure of gustiness and pollutant concentration. The concentration of PM$_{2.5}$ had a significant decreasing trend (blue shading in figure 5) when $R_{u_gw_g} > 0$, while the concentration of PM$_{2.5}$ showed an increasing trend when $R_{u_gw_g} < 0$. Due to the strong randomness of air flow in the ABL, not all $R_{u_gw_g}$ values were greater than zero during the declining period of the PM$_{2.5}$ concentration.
The coherent structure is closely related to turbulence transport. The upward and downward sweeping motions are considered to be the main part of the coherent structure (Katul and Chu, 1998), so the coherent structure would also directly affect the pollutant concentration in the UCL.

The pollutants with higher concentrations in the UCL more easily diffuse upward when \( u_g > 0 \) and \( w_g > 0 \) and thus can be removed with the help of the larger wind speed above the canopy. Generally, the pollutant concentration decreases with height. The pollutants outside the UCL were more likely to diffuse downward and penetrate the canopy when \( w_g < 0 \) and \( u_g < 0 \). At this time, the relatively clean atmosphere infiltrates the canopy, diluting the pollutants in the canopy. In addition, combined with \( u_g \) smaller than zero, the large-scale basic air flows tend to decrease, which is not conducive to the mixing of pollutants in the lower layer, and the concentration of pollutants at the local observation site is therefore reduced.

The concentration of PM\(_{2.5}\) dropped from nearly 250 \( \mu \text{g m}^{-3} \) to a few micrograms per cubic meter within a few hours on 3 Dec, and this phenomenon was mainly caused by the transformation of the synoptic system over the observation area (Wu et al., 2017). When the pollutant concentration began to decline, \( R_{u_g w_g} \) at 8 m changed to a positive value early. \( R_{u_g w_g} \) mainly exceeded 0.5 on 3 Dec and 4 Dec, with a maximum of about 0.57.

The time series of \( R_{u_g w_g} \) at 8 and 47 m was very close, and these two layers are greatly affected by the forcing of the UCL. \( R_{u_g w_g} \) at 140 m also changed to positive value during the rapid removal of pollutants. Compared with \( R_{u_g w_g} \) at 8 and 47 m, the variation of \( R_{u_g w_g} \) at 140 m was slightly different from 29 Nov to 2 Dec, indicating that the coherent structure at 140 m is less affected by the UCL. \( R_{u_g w_g} \) at 280 m also changed to positive during the rapid clearance period. From 29 Nov to 2 Dec, \( R_{u_g w_g} \) at 280 m basically fluctuated near zero. Therefore, the correlation between \( R_{u_g w_g} \) at 280 m and the pollutant concentration was relatively low. On 3 and 4 Dec with strong winds, \( R_{u_g w_g} \) at the four heights mainly changed into positive values, mainly affected by the synoptic system.

Figure 6 shows a schematic representation from the rapid removal of pollutants of the UCL. Even under strong winds, horizontal wind in the urban canopy is still small, and the pollutants are greatly blocked by various buildings within the UCL. Pollutants are transported vertically above the UCL through a combination of gustiness and its coherent structures, and then blown away quickly by the larger basic air flows above the canopy.

**Conclusions**

Compared with the slow increase in the concentration of PM\(_{2.5}\), its removal process was very rapid despite the great blocking effects of various buildings in the city. In this study, the important role of gust-wind and its coherent structures in the rapid removal process of urban air pollutants is analyzed. The three wind component
fluctuations $u'$, $v'$, and $w'$ are decomposed by third-order Daubechies wavelet transformation and the gustiness was extracted by calculating the fractional dimensions.

This study selected a pollution process in Beijing from 29 Nov to 4 Dec 2017. The small horizontal wind at 8 m and vertical velocity ($|w| < 0.1 \text{ m s}^{-1}$) within the tower layer were very favorable to the accumulation of pollutants. In the early rapid decrease in the concentration of surface pollutants (00:00–03:00 on 3 Dec), $V$ in the high layer increased, but $V$ at 8 m did not increase. Descending motions dominated at the lower layer of the tower (8 and 16 m). The vertical speed at 47 m wa approximately 0 m s$^{-1}$, and it changed into an updraft above 80 m. Therefore, in addition to the strong horizontal winds, the pollutants in the high layer could also be removed quickly through ascending movements. However, for the lower layer of the UCL with more pollution sources, it is obvious that the pollutants in the lower layer cannot be quickly removed by means of downdrafts. In addition, the obstruction of buildings, houses, trees and so on in the UCL to the air flow could seriously reduce the diffusion and removal efficiency of pollutants at the low layer by means of basic air flows. Therefore, basic air flows contribute little to the rapid removal of pollutants in the lower layer of UCL.

The averaged wind speed has little indicative significance during the small declines in the continuous increasing trend of the concentration of PM$_{2.5}$ from 1 to 2 Dec. However, at this time, friction velocity $u_{*g}$ and the concentration of PM$_{2.5}$ show a clear inverse correlation, $u_{*g} \approx u_{*g}$, and $u_{*g}$ was the most obvious factor influencing the concentration of PM$_{2.5}$ with an inverse correlation coefficient of $-0.56$.

Generally, there was no significant difference in $u_{*g}$ at the four heights, basically changing synchronously. Due to the great disturbances on air flows caused by various buildings, trees and other obstacles in the UCL, the value $|w_{*g}|$ on the lower layer of the tower was significantly higher than that on the upper layer, especially at 47 m. $u_{*g}$ and $w_{*g}$ have obvious negative correlations with the concentration of surface PM$_{2.5}$, especially at 8 and 47 m. $\bar{w}$ at the lower layer of the tower was negative during the removal period, and the horizontal wind in the canopy was also blocked by the buildings and vegetation in the canopy. Therefore, the removal process of pollutants in the lower layer within the UCL was mainly dominated and affected by gust-wind.

The coherent structure of gustiness and the concentration of pollutants have a close relationship.

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Based on the above analysis, we proposed a physical conceptual model of the rapid removal process of urban air pollutants within the UCL and reveal the important role of gustiness and its coherent structure.
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Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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