Dear reviewer,

We really appreciate your revealing questions and comments. These constructive opinions help to improve our work to a great extent. We did our best to respond to these comments one by one. We hope the reviewer would approve of our following response. Details are listed as follows

The authors investigated the influence of turbulence structure and urbanization on the heavy haze pollution process, and did a very detailed analysis. The results provide valuable information on the interaction between pollution and turbulence flux and the differences between urban and rural area during heavy haze time. However, further study according to following comments is needed:

Major comments:

1) the authors mentioned “the impact of the pollution process on suburb areas is much greater than that on urban areas. Urbanization seems to help reduce the consequences of pollution” in the end of abstract. What are the dynamic/physical mechanism behind that? What is the difference in PM2.5 source at urban areas and suburb areas?

Response: We really appreciate your questions. We want to introduce more details about these two sites and try to explain the second question before answering the dynamic/physical mechanism behind the sentence. Suburban site is located at locally flat underlying surface, as shown in Fig.1, 20 km away from the urban site. At this distance, we believe that the impact of the large-scale weather situation on both sites is consistent. Recent studies have shown that Beijing's winter pollution process can be divided into pollutant transport stage and accumulation stage (Zheng et al., 2015a; Liu et al., 2013; Guo et al., 2014; Zhong et al. 2017; Zhong et al., 2018). Some studies have shown that emissions from outside Beijing can contribute 28–70% of the ambient $PM_{2.5}$ concentrations in Beijing (An et al., 2007; Streets et al., 2007; Z. Wang et al., 2014; Chang et al. 2018). During the period we are concerned, as shown in Fig. 2, Zhong et al.'s research indicates that the pollution process is composed of the transportation of pollutants by southerly wind and accumulation of pollutants under the static wind (wind speed less than 2 m/s). Pollutant transport is dominated by large-scale weather processes, so the contribution to the source of $PM_{2.5}$ due to transport can be considered to be substantially consistent between the two sites separated by 20 km. In the accumulation stage of pollutants, it can be seen that the wind speed is less than 2 m/s in the layer below 1 km, and there is no longer large-scale transportation. At this time, the contribution of the local source may be highlighted. Due to the regulatory measures such as factory shutdowns implemented by the government in the fall of 2016 (“Bulletin on the State of China's Ecological Environment in 2016”), there are few major industrial sources in Beijing during our research phase, and there are only a small number of residential sources. In fact, in the government regulation in 2017, the residential sources had also been strictly controlled. Although the suburban site is located in a relatively flat farmland, it is still in the vicinity of the Changping county. Therefore, the residential sources between the two sites may be different, but this difference is not significant compared to the large number of sources in the transportation process. In summary, we think that the sources of $PM_{2.5}$ of the two sites are generally consistent.

Figure 1 Google earth map of the suburban site within a range of approximately 1 km.

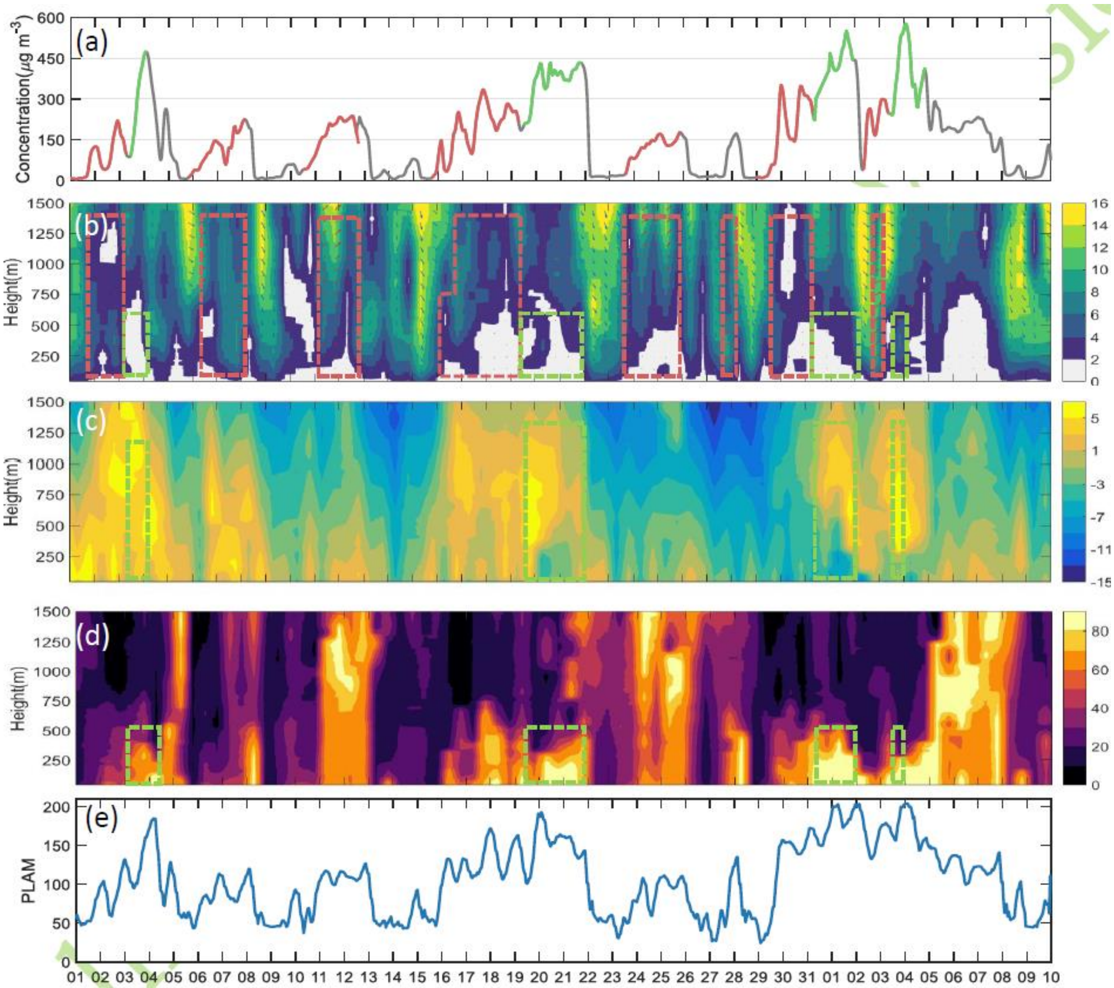

Figure 2 Temporal variations in $PM_{2.5}$, PLAM, and vertical distributions of meteorological factors from 1 December 2016 to 10 January 2017 by Zhong et al. (2017), their Fig.1. (a) $PM_{2.5}$ mass concentration, (b) wind vector and wind velocity (shading; m s^{-1}), (c) temperature (shading; ℃), (d) RH (shading; %), and (e) PLAM. Red boxes correspond to original/transport explosive growth processes, while green boxes correspond to subsequent/cumulative explosive

growth processes.

Due to the close distance between the two stations, the large-scale weather background is consistent, and the underlying surface of the suburban site is locally flat, so the flat terrain of the suburb is used as a reference. We consider the turbulence structure over the flat surface of the suburban area as the normal state in this area under such weather and pollution source conditions, then the urban turbulent structure is influenced by urbanization. Next, we want to discuss the dynamic mechanism behind this sentence from two aspects. First, the LIST (intermittent intensity) at the suburban site is smaller (stronger) than that at the urban site (as shown in Fig.7 and Fig.8 in the manuscript). The value of $V_{smeso}(V_{turb})$ at the urban site is slightly smaller (larger) than that at the suburban site. All of these mean that the proportion of turbulence in the acquired signal at the urban site is stronger than that at the suburban site which was caused by rough underlying surface mainly. So from the turbulence intermittency perspective, the value of the LIST at the urban site is significantly greater than that at the suburban site, which means that the dynamic effect of the underlying surface of the urban area is stronger than that of the flat underlying surface of the suburban area. That is correspond to the previous studies on atmospheric turbulence over cities, such as, Roth (2000) concluded that there was an intense shear layer near the top of the city canopy which provided increased mechanical mixing in his review paper. Second, the change in turbulent flux during the pollution process also showed a difference in turbulence between the two sites. As shown in Fig.11 in the manuscript, the sensible heat flux, latent heat flux, momentum flux, and TKE in the urban and suburban sites are all weaken when pollution occurs. More importantly, the reduction of turbulence exchange during the pollution period in suburban sites is greater, compared to urban sites. In other words, the impact of the pollution process on the suburbs is much greater than that on the urban area. As mentioned earlier, we consider the turbulent structure over the suburb site as the normal state in this area under such weather and pollution conditions, the change in the underlying surface of the urban site (the dynamic effect of complex terrain and the heat island effect caused by human activities) leads to a greater resistance to the weakening effects of turbulent exchange caused by pollution. To sum up two points, the change in turbulence structure brought about by urbanization has a weakening effect on the consequences caused by pollution.

The weaker turbulence intermittently caused by urbanization provides stronger turbulent flow during heavy pollution, so from the perspective of turbulent structure, the complexity of the urban underlying surface provides better turbulent transfer conditions compared to flat underlying surface.

However, maybe this sentence is somewhat misleading when it appears alone. We changed the expression to “The turbulent effects caused by urbanization seems to help reduce the consequences of pollution under the same weather and pollution source condition, because the turbulence intermittency is weaker and the reduction of turbulence exchange is smaller over urban underlying surface.” in the abstract.

According to your comments, the following changes were made:

Figure 1 in the manuscript has been modified to reflect the condition of the underlying surface around the two sites. The new Fig. 1 for the manuscript is shown as Fig. 3 here:

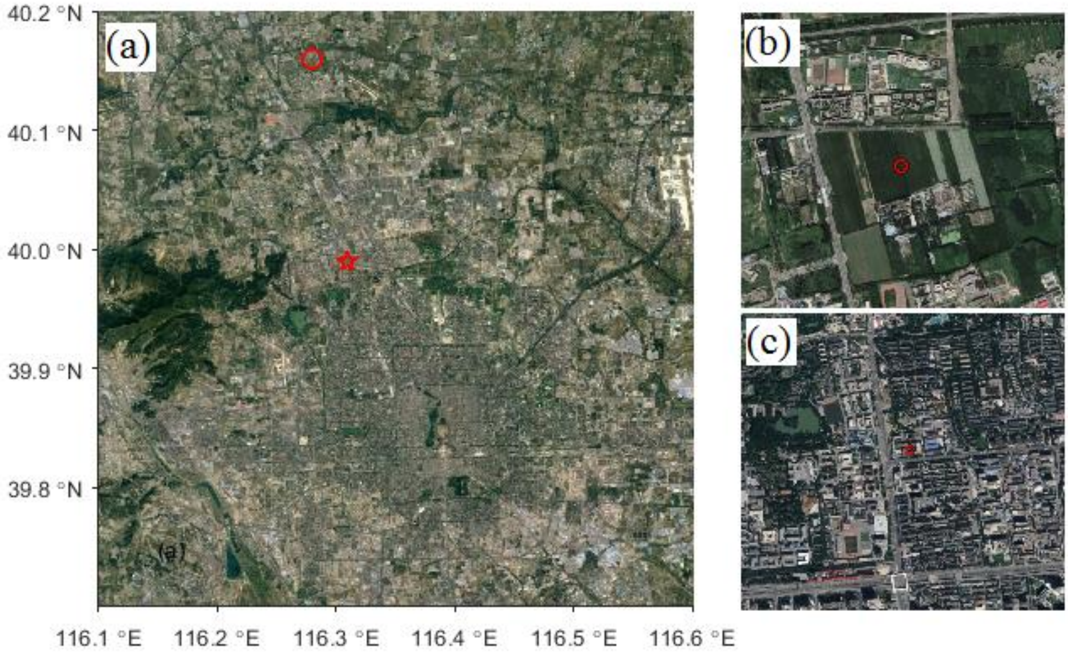

Figure 3 Figure 1 in the manuscript: Google Earth map of the observation sites in Beijing: (a) the observation site located in the urban underlying surface region (marked by the red pentagram) and the observation site located in the suburban underlying surface region with a flat terrain (marked by the red circle). The corresponding terrains (within a range of approximately 1 km) around the observation sites are shown in (b) and (c), respectively.

Details of the suburban site are added on page 3, lines 29-30:

"Data over a locally flat underlying surface were collected at a continuous measurement site (40.16° N, 116.28° E) in the Beijing suburb. The observational site was set up in the middle of a vast and horizontal farmland, in the vicinity of the Changping county."

We added a description of the location relationship between the two sites on page 4, lines 20-32:

"Suburban site is 20 km away from the urban site. At this distance, the large-scale weather background is consistent. As flat terrain of the suburban site, it was used as a reference. The sources of $PM_{2.5}$ of the two sites are generally consistent."

We changed the description in the abstract on the first page, line 25-28:

"The turbulent effects caused by urbanization seems to help reduce the consequences of pollution under the same weather and pollution source condition, because the turbulence intermittency is weaker and the reduction of turbulence exchange is smaller over urban underlying surface."

The last paragraph of the conclusion was reorganized, on page 26, lines 12-19:

"Due to the close distance between the two stations, the large-scale weather background is consistent, and the suburban site is locally flat, so the turbulent structure over the flat surface of the suburban area is considered as the normal state in this area under such weather and pollution source conditions, then the urban turbulent structure is influenced by urbanization. More importantly, the reduction of turbulence exchange during the pollution period in suburban sites is greater, compared to urban sites. In other words, the impact of the pollution process on the suburbs is much greater than that on the urban area. The change in the underlying surface of the urban site (the dynamic effect of complex terrain and the heat island effect caused by human activities) leads to a greater resistance to the weakening effects of turbulent exchange caused by pollution."

2) The heights of two observational sites are different, one at 25m and the other at 10m. What are differences of temperature, wind speed, specific humidity and PM2.5 caused by the height difference?
The authors used one point to represent the whole Beijing, how much is the difference in surface temperature, wind speed, specific humidity and PM2.5 at different locations of urban Beijing?

Response: Thanks for your question. The problem you mentioned does exist. However, this manuscript focuses on the difference of the turbulent structure and exchange between surface and atmosphere between two sites which have different underlying surfaces and are not far apart under control of the same weather and pollution source background, the meteorological elements are only the background for the process of pollution and not the focus of this work. In the manuscript, the Fig. 2 was only used to reflect the overview of the pollution process in two sites. The sentence which describes the difference between two sites is on page 6, line 15-17. Considering the present study of turbulence characteristics, we have deleted this sentence. While for turbulence flux in the two sites, they are comparable because in our work both sites were thought to be located within the surface layer, i.e. the constant flux layer.

The structure of the atmospheric boundary layer on different underlying surfaces is shown in Fig. 4. In urban boundary layers, the constant flux layer is generally located above the urban canopy (Roth, 2000; Wood 2010;). It is generally believed that the turbulent flux in the surface layer varies little with height, and M-O similarly is applicable (Arnfield, 2003). Roth (2000) provided a comprehensive, critical review of turbulence observations over cities, which included many experiments (Kato et al. 1992; Oikawa, 1993; Oikawa and Meng, 1995; Oikawa et al., 1995; Casadio et al. 1996; Xu et al., 1996; Feigenwinter et al.,1999) that the height of the observation is above the height of dominant roughness elements. The same is true of research on urban boundary layers in recent years (Weber et al., 2010; Fortuniak et al. 2013; Nordo et al. 2013; Ao et al., 2016;). The height of the urban observation site is 25 m. As shown in Fig.5, the buildings around the site are neat and uniform, average building height is 20 m. So the urban site is thought to be located within the surface layer. The suburban site is locally flat and its observation height is 10 m, which is also located in the surface layer. Because of the constant flux assumption in surface layer, the turbulence characteristics between the two sites is comparable. For meteorological elements, although both sites are within the surface layer, the height of observation will have an inevitable impact on their value. However, the differences in meteorological elements brought by different observational heights are not the focus of this manuscript, and have no impact on the conclusions.

It is unreasonable to use one point to represent the whole Beijing, there are differences in meteorological elements between different stations due to differences in underlying surfaces. The buildings around the urban site are evenly distributed, and the observations at the site can represent the typical underlying surface conditions of this part of the city, and the comparison with the flat underlying surface of the suburbs is also effective.

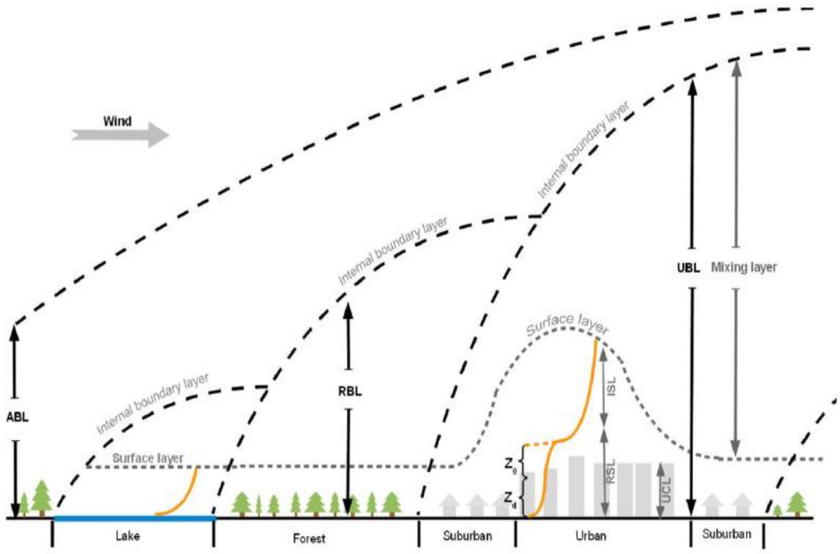

Figure 4 Schematic structure of the atmospheric boundary layer (ABL) that comprises internal boundary layers between dominant surface-cover types (lake, forest, suburban, urban; not to scale) by Nordbo (2012), their Fig. 3. RBL { rural boundary layer, UBL{urban boundary layer, RSL{roughness sublayer, ISL{inertial sublayer, UCL{urban canopy layer. Logarithmic wind profiles in the near-neutral surface layers (orange) are shown with the displacement height (z_d) and roughness length (z_0) over the urban surface. The urban boundary-layer structure is adapted partly from Oke (1987).

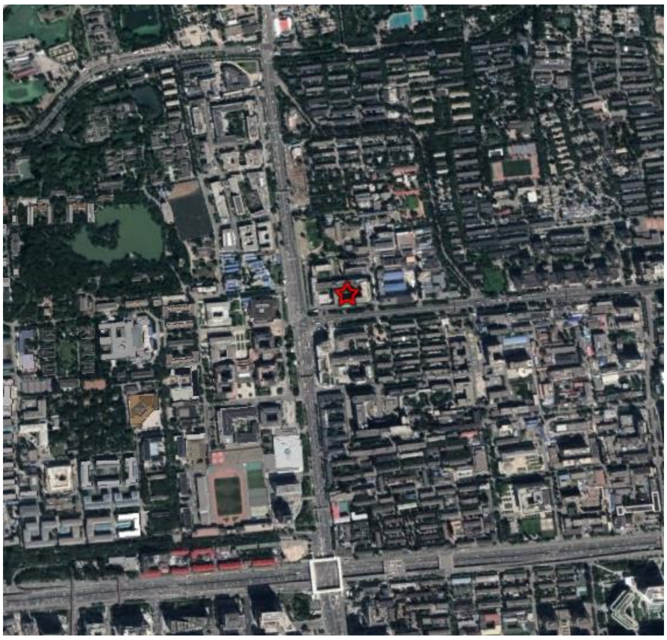

Figure 5 Google earth map of the urban site within a range of approximately 1 km.

According to your comments, the following changes were made:

A little detail about the suburban site is added on page 3, line 30:

"The EC system was mounted at a height of 8.3-m above ground which was located within the surface layer"

Details of the urban site are added on page 4, lines 9-10:

"The buildings around the site are neat and uniform, average building height is 20 m. So observations at the urban site are located within the surface layer."

A description of the turbulence quantities for both sites is added on page 4, lines 23-24:

"Since the observations at both sites are located in the surface layer, i.e. the constant flux layer, the values of turbulence flux are comparable."

The sentence which describes the difference between two sites is on page 6, line 15-17, we have deleted this sentence because the comparison between two sites is meaningless and has no impact on our work. The sentence is shown as follows:

"The horizontal wind speed, virtual temperature and water vapor at the suburban site are greater, lower, and higher than those at the city site, respectively."

3) The authors pointed out the differences between clear and pollution days in the mass and energy exchanges at surface and concluded that the pollution inhibits the mass and energy exchange at surface. However, weak vertical mixing and surface wind can cause pollutants to accumulate and lead to heavy pollution.

Response: You're right that weak vertical mixing and surface wind can cause pollutants to accumulate and lead to heavy pollution. In fact, the relationship between the turbulence exchange and pollution accumulation is a kind of positive feedback. In the early stage of pollution, with the cooperation of the weather system, the southerly wind transports pollutants from the industrial area to the Beijing area

(Zheng et al., 2015a; Liu et al., 2013; Guo et al., 2014). In the process of gradual development of pollution, the weather system is stagnant, and the southerly wind transport is weakened or even disappeared. At this time, the small wind condition causes the weakening of the turbulent dynamic effect, and due to the accumulation of pollutants in the initial stage of pollution, the high aerosol loading greatly cool the surface by reducing surface insolation caused by scattering and absorption of sunlight in the atmosphere (Forkel et al., 2012; Ding et al., 2016; Petaja et al., 2016; Zhong et al., 2018). Therefore, the turbulent thermal effect is weakened, the inversion layer develops, and turbulent exchange is suppressed. The weakening of turbulent exchange has caused further accumulation of pollution. The accumulation of pollutants and the weakening of turbulent exchange are positive feedback processes that interact and promote each other before the static weather situation is broken.

Minor comments:

1)Figure 2a only has one line, but 2b and 2c have two lines. Figure 2a should have two line to show the results from two stations.

Response: Thank you for your comments. The suburban site did not have observations of particulate matter. The observations of $PM_{2.5}$ at urban sites are used to represent the evolution of the entire pollution process, as this manuscript focuses on pollution processes rather than specific values. As mentioned in the answer of the first major comment, the sources of $PM_{2.5}$ of the two sites are not much different. In fact, the trends in contaminants across all environmental monitoring sites throughout the Beijing area are consistent, although there are some numerical differences. We choose three environmental monitoring stations, Changping (116.23°N, 40.22°E), Haidian (116.29°N, 39.99°E) and Daxing (116.40°N, 39.72°E), to prove that. The time series of mass concentration of $PM_{2.5}$ at the three environmental monitoring stations are shown in Fig. 6, their locations are shown in Fig. 7.

The data of $PM_{2.5}$ used in this manuscript is mainly to show the corresponding relationship between the trend of pollution development and intermittent turbulence, as shown in Fig.7 and Fig.8 in the manuscript. For the purposes of this work, the difference in the magnitude of the $PM_{2.5}$ values between the two sites does not affect the results. And because the pollution data from environmental monitoring sites have a large number of missing measurements during the study period, so we still use the observations from the urban site to represent the evolution of the entire pollution process.

An explanation of the data problem of $PM_{2.5}$ is added to Section 2, page 4, lines 21-22:

"The observations of $PM_{2.5}$ at urban sites are used to represent the evolution of the entire pollution process, as this study focuses on pollution processes rather than specific values."

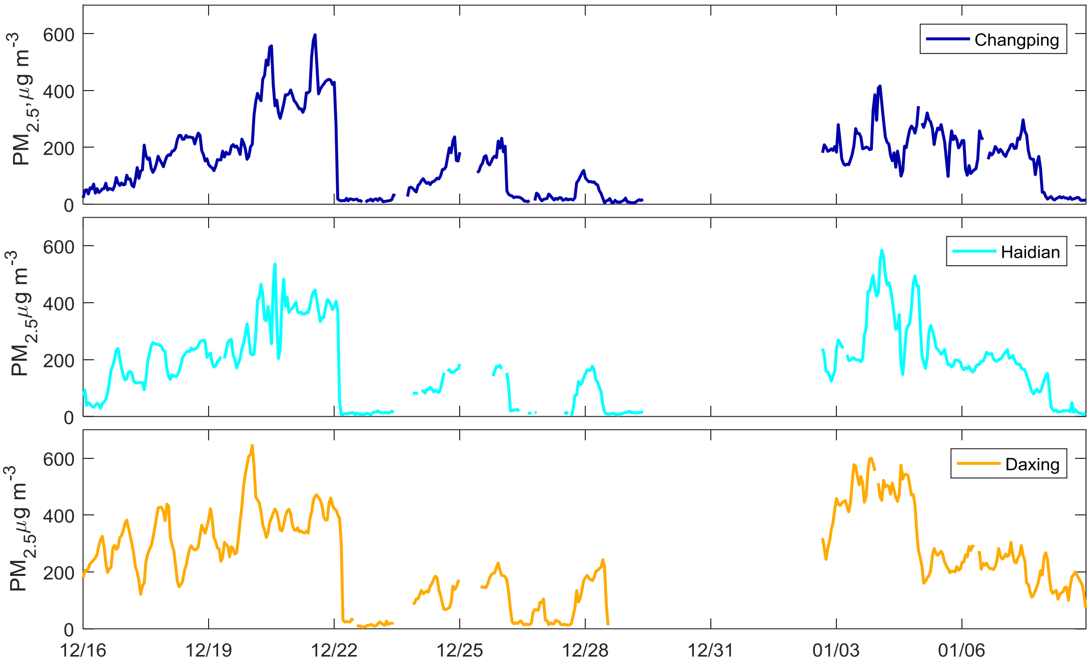

Figure 6 The time series of mass concentration of $PM_{2.5}$ at the three environmental monitoring stations in Beijing.

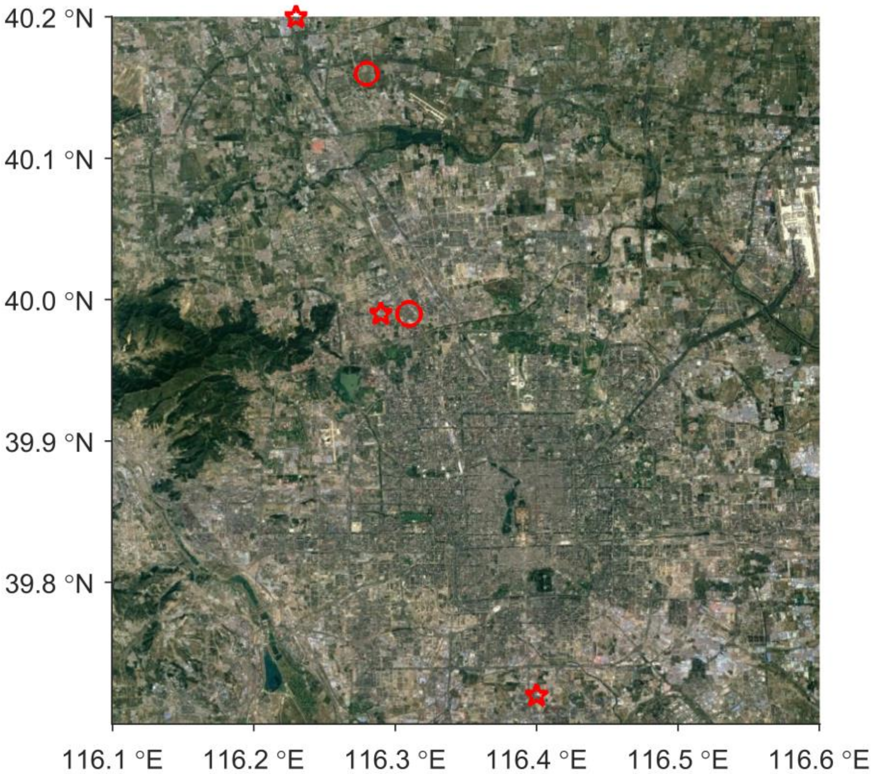

Figure 7 Google Earth map of the observation sites in Beijing. The locations of the three environmental monitoring stations are marked by the red pentagram. The urban and suburban sites in manuscript are marked by red circle.

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