Dear Editor and Reviewers,

Thank you for your comments concerning our manuscript entitled "Uncovering the Impact of Urban Functional Zones on Air Quality in China". Those comments are all valuable and very helpful for revising and improving our paper, as well as the important guiding significance to our researches. We have studied comments carefully and have made correction which we hope meet with approval. Revisions are indicated within the text using track changes. **All of the responses have been addressed in blue and revisions have been addressed in red as following file of response letter**, and page numbers and line numbers in the response are based on the clean version. In the following, we include a point-by-point response to the comments.

Thank you and best regards.

Yours sincerely,

Wenchao HAN & Yang WANG

Responses to RC1

Comment 1: The annotation of references is not standardized, for example, "Zhang et al., 2022c" on line 26 should be "Zhang et al., 2022a".

Response:

Thanks! We have revised the annotations of the references.

Comment 2: This translation of "the Three-Year Action Plan for Winning the Blue Sky Defense Battle" on line 117 and "Suzhou and Qingdao have the most residential zone sites," on line 186, etc. is inappropriate, which is too Chinglish.

Response:

Thank you for your suggestion. To ensure a more scientifically accurate translation of the "Three-Year Action Plan for Winning the Blue Sky Defense Battle," we conducted an extensive review of relevant literature. In doing so, we specifically examined three representative papers published in reputable journals: *Environmental Science & Technology*, *Nature Communications*, and *Environmental Science and Ecotechnology*. Therefore, this translation is consistent with the terminology presented in these publications (Liu et al., 2023; Shi et al., 2022; Zheng et al., 2022).

Reference

Liu, Y., Geng, G., Cheng, J., Liu, Y., Xiao, Q., Liu, L., Shi, Q., Tong, D., He, K., and Zhang, Q.: Drivers of Increasing Ozone during the Two Phases of Clean Air Actions in China 2013–2020, Environ. Sci. Technol., 57, 8954–8964, https://doi.org/10.1021/acs.est.3c00054, 2023.

Shi, Q., Zheng, B., Zheng, Y., Tong, D., Liu, Y., Ma, H., Hong, C., Geng, G., Guan, D., He, K., and Zhang, Q.: Co-benefits of CO2 emission reduction from China's clean air actions between 2013-2020, Nat Commun, 13, 5061, https://doi.org/10.1038/s41467-022-32656-8, 2022.

Zheng, Y., Xue, T., Zhao, H., and Lei, Y.: Increasing life expectancy in China by achieving its 2025 air quality target, Environmental Science and Ecotechnology, 12, 100203, https://doi.org/10.1016/j.ese.2022.100203, 2022.

Comment 3: What is the meaning of this paragraph on line 117-121 in "2.1 Study area"? Why is it placed here?

Response:

We mentioned the concept of "three key areas" in **Section 3.4.1**, therefore we provided a relevant introduction within the study area. To enhance clarity and coherence, these lines have been replaced to **Section 3.4.1**.

Comment 4: The production of Figure 1 is not standardized. Because the latitude and longitude grid has already been marked in Figure 1, there is no need for a compass.

Response:

Thanks for pointing this out. We have revised Figure 1 in accordance with your feedback and the suggestions provided by another reviewer, as illustrated below.

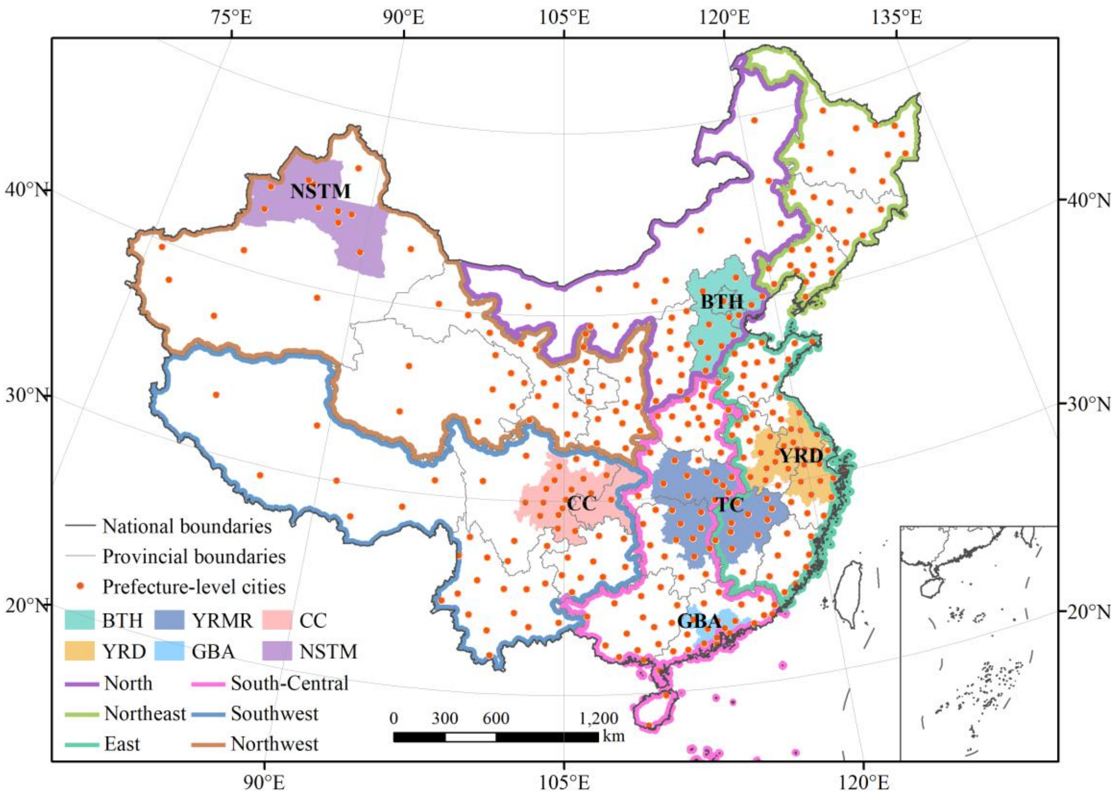

Figure 1. The location of study area and the distribution map of six geographical regions and six major urban agglomerations. BTH: Beijing-Tianjin-Hebei urban agglomeration; YRD: Yangtze River Delta urban agglomeration; TC: Triangle of Central China; GBA: Greater Bay Area urban agglomeration; CC: Chengdu-Chongqing urban agglomeration; NSTM: Northern Slope of Tianshan Mountains urban agglomeration.

Comment 5: "2.3.1 Data preprocessing" should be placed in "2.2 Data sources".

Response:

We appreciate your suggestion. For this study, data preprocessing is a crucial step that we believe should be regarded as a distinct component. We have carefully revised and expanded Section 2.3. For more details, please refer to Comment 6.

Comment 6: I haven't found any specific data analysis or research methods in "2.3

Data analysis methods".

Response:

Thank you for your advice. We would like to clarify that, rather than employing specific data analysis methods, this study places a greater emphasis on data statistics. Therefore, to ensure clarity and avoid any potential ambiguity, we have made the following revisions: "2.3 Data analysis methods" has been removed, the former 2.3.1 has been renumbered to 2.3, and the former 2.3.2 has been renumbered to 2.4. And we have made several specific adjustments to "2.4 Data analysis process". Section 2.4 has been restructured into two distinct subsections: 2.4.1 Overlay Analysis and 2.4.2 Data Statistics. In particular, in "2.4.2 Data Statistics", we have added the formula for calculating the variation trend of pollutant concentrations, which enhances the clarity and completeness of our data interpretation. The details of these revisions can be found on manuscript **Lines 156-193**.

2.4 Data analysis process

2.4.1 Overlay Analysis

Overlay analysis is a spatial analysis technique that involves combining multiple geographic layers to reveal spatial relationships and attribute associations between different elements. In general, overlay analysis is mainly used to integrate various types of spatial data, identifying intersecting, union, or difference areas to provide a foundation for subsequent analyses. Common operations include Intersect, Union, Erase, and Spatial join. In this study, ArcGIS was employed to overlay the latitude and longitude data of the sites with the urban functional area data, allowing for the identification of the functional area category for each site through spatial connections. This process facilitated the addition of new functional area attribute information to the site data. Using a similar methodology, the longitude and latitude data were overlaid with DEM grid data to obtain elevation information for each station. This integration of spatial and attribute data not only provided a more nuanced understanding of the spatial distribution of the sites but also laid the groundwork for further investigations into the relationships between site characteristics and urban functional zones.

2.4.2 Data statistics

In this study, MATLAB was employed as the primary computational tool to develop a customized code for batch processing the pre-processed pollutant concentration data obtained from various monitoring sites. This approach facilitated the efficient calculation of daily, monthly, and annual mean values for six key pollutants ($PM_{2.5}$, PM_{10}, SO_2, NO_2, O_3, and CO) at each site, thereby providing a comprehensive temporal overview of pollutant concentrations. Following the temporal analysis, the study proceeded to spatially categorize the data based on functional area classifications. The specific operation method is to establish the site index for each functional area. The corresponding pollutant concentration data for each functional area was extracted based on this site index, leading to the classification of pollutant concentration data across different functional zones. Finally, the average concentrations and variation trend of the six pollutants within each functional area were computed across various spatial scales, including six geographical regions, six urban agglomerations, and different altitudes. The variation trend of pollutant concentrations was characterized by the relative rate of decline, with the specific formula presented as follows.

$$Trend\,(\%) = \frac{(x_{2022} - x_{2017}) \div 5}{\sum x_i \div 6} \times 100\%$$

where i represents the year (i = 2017, 2018, ……, 2022), x represents the average concentrations of six pollutants.

Comment 7: "3.4 Analysis of influencing factors" only includes three single factor analyses, which is too simple.

Response:

The reviewer raises a great point. These three factors are considered of great importance to influence the air pollution of different function zones. The reasons why we focus on governance measures, altitude, and weekdays are as follows: The selection of governance measures, by comparing the three key areas with the other areas, aims to highlight the differential impacts resulting from different management intensities in various regions. There are significant differences in meteorological conditions across different altitude areas, and the scale and development characteristics of cities are closely related to altitude, which has an undeniable impact on the research results.

Moreover, different functional zones have different functions, and there are significant differences in human activities between weekdays and non-weekdays, which directly affect the emission situations of different functional zones.

Following your suggestion, we have added the impact of urban scale, as detailed in Comment 9. In addition, the distribution of functional zones within a city is intricate (as shown in Figure R1), and there may be interactions between different functional zones. To accurately quantify the relative contributions of various factors, extremely refined model simulations are required, but this work still faces many challenges at present. This is expected to be a remarkably valuable and important subject of study in the future. Your suggestion is indeed valid, prompting us to incorporate a limitation into our discussion (**Lines 595-598**): "Furthermore, this study has only analyzed the influence of several individual factors without conducting a comprehensive evaluation of their relative contributions. In future research, as simulation technologies continue to advance, we will strive to conduct a more thorough analysis of these integrated effects."

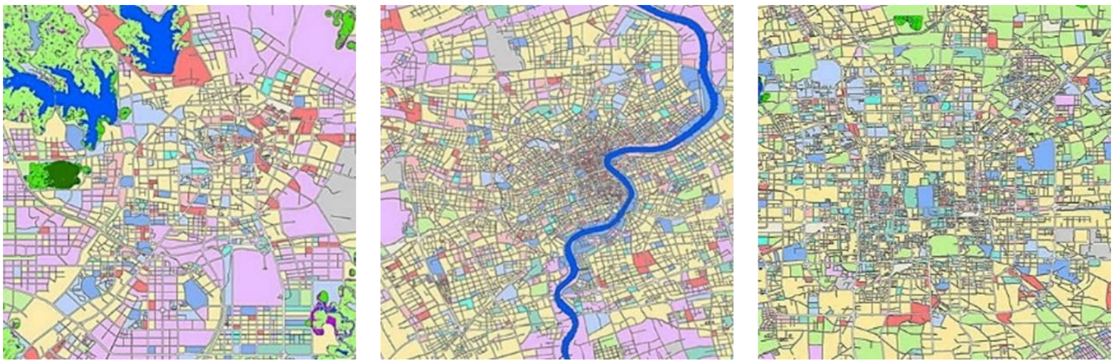

Figure R1. Distribution of urban functional zones.

Comment 8: Overall, this manuscript contains too much data description and lacks data analysis, especially discussion.

Response:

We agree with your valuable comment. In the manuscript, several sections did lack sufficient elaboration. As suggested, we have incorporated additional explanations and quantification description in the discussion to address these deficiencies.

"Furthermore, in terms of industrial zone, the SO_2 concentration of BTH obviously surpasses that of other urban agglomerations (P < 0.01), reaching 15.6 μg/m³. The industrial structure of BTH is dominated by heavy industry, with industrial land use exhibiting a high degree of concentration, such as steel, chemical industry, building materials, etc. These sectors serve as the primary contributors to SO_2 emissions." **in Section 3.3.2 Lines 395-399.**

"The reduction in particulate matter and NO_2 is most significant at high altitudes (above 2000 m), with diminishing improvements observed between 0-2000 m as altitude increases. Meanwhile, the improvement of SO_2 and CO decreases with the increase of altitude above 500 m. These phenomena are primarily influenced by a combination of factors, including emission sources, dilution effects, meteorological conditions, and chemical reactions. In high-altitude areas, meteorological conditions such as wind speed and turbulence are conducive to the dispersion and dilution of pollutants, thereby promoting the improvement of particulate matter and NO_2 concentrations (Román-Cascón et al., 2023). Additionally, SO_2 and CO in the atmosphere can be chemically transformed into other pollutants, such as sulfate aerosols and organic aerosols. In higher-altitude regions, the rates and extents of these chemical reactions may change, affecting the degree of improvement in SO_2 and CO concentrations (Quan et al., 2021). In low-altitude regions (below 1000 m), the reduction of these pollutants in transportation zone was minimal. Conversely, in high-altitude regions (above 1500 m), a significant decrease in these pollutants was observed in both residential and industrial zones. This may be due to the higher density of vehicular traffic in lower altitude areas, coupled with reduced human activity in higher altitude regions. The low-altitude regions are characterized by dense populations and substantial traffic flow, which lead to concentrated and high-intensity vehicle exhaust emissions. Consequently, a substantial number of pollutants, including particulate matter, nitrogen oxides, and volatile organic compounds, are continuously released into the atmosphere. This results in a high baseline concentration of pollutants, making it challenging to achieve significant improvements in air quality (Lopez-Aparicio et al., 2025). In contrast, high-altitude areas have limited scales and quantities of residential and industrial land. As a result, the total volume of pollutants emitted from human activities is relatively small. Therefore, under the favorable influence of natural conditions, the concentration of pollutants in these regions is more amenable to substantial improvement." **in Section 3.4.2 Lines 464-482**.

As for the other parts, there was a detailed discussion and analysis. For example: "The main reason is that following the implementation of policies such as the "Clean Winter Heating Plan for Northern China (2017–2021)" and the "Three-Year Action Plan for Winning the Blue Sky Defense Battle", the government intensified control over industrial pollution, promoted clean production in enterprises, implemented clean heating measures in residential areas, and encouraged the use of clean fuels like natural gas and electricity." **in Lines 227-231**. "The primary cause of these seasonal changes is the variation in particulate matter concentration within the environment, particularly when there is low removal efficiency of industrial dust with high emissions, leading to an increase in this seasonal trend accordingly. Thus, the emission levels of particulate matter from industrial and transportation zones surpass those from other functional zones, resulting in conspicuous seasonal fluctuations. The greater seasonal fluctuation of NO_2 and O_3 observed in residential zone and industrial zone compared to other functional zones can be attributed to activities such as heating and coal burning during winter, which elevate the production of nitrogen oxides along with ozone precursors within the atmosphere." **in Lines 277-284**. "The increased consumption of coal and biomass for residential living and the high proportion of people traveling on weekends lead to significantly higher particulate matter emissions from human activities on residential zone and transportation zone on weekends than on working days. In recent years, the influence of the pandemic and the implementation of the industrial "off-peak production" policy have caused certain factories to operate normally on weekends, potentially contributing to the heightened weekend concentrations of PM in industrial zone." **in Lines 320-325**. "This disparity can be attributed to North and Northwest China being the epicenter of China's traditional industrial base, endowed with abundant coal and mineral resources. The presence of numerous large-scale enterprises, including coal-fired power plants, the steel industry, and the non-ferrous metal industry, contributes to significant pollutant emissions. Furthermore, the reliance on coal combustion for heating during the winter months exacerbates pollutant emissions." **in**

Lines 346-349.

Reference

Lopez-Aparicio, S., Grythe, H., Drabicki, A., Chwastek, K., Toboła, K., Górska-Niemas, L., Kierpiec, U., Markelj, M., Strużewska, J., Kud, B., and Sousa Santos, G.: Environmental sustainability of urban expansion: Implications for transport emissions, air pollution, and city growth, Environment International, 196, 109310, https://doi.org/10.1016/j.envint.2025.109310, 2025.

Quan, J., Wang, Q., Ma, P., Dou, Y., Liao, Z., Pan, Y., Cheng, Z., Ding, D., and Jia, X.: Secondary aerosol formation in cloud serves as a vital source of aerosol in the troposphere, Atmospheric Environment, 253, 118374, https://doi.org/10.1016/j.atmosenv.2021.118374, 2021.

Román-Cascón, C., Yagüe, C., Ortiz-Corral, P., Serrano, E., Sánchez, B., Sastre, M., Maqueda, G., Alonso-Blanco, E., Artiñano, B., Gómez-Moreno, F. J., Diaz-Ramiro, E., Fernández, J., Martilli, A., García, A. M., Núñez, A., Cordero, J. M., Narros, A., and Borge, R.: Wind and turbulence relationship with NO2 in an urban environment: a fine-scale observational analysis, Urban Climate, 51, 101663, https://doi.org/10.1016/j.uclim.2023.101663, 2023.

Comment 9: When analyzing the impact of different urban functional zones on air quality, the authors overlooked the scale effect of different functional zones, especially the scale effect of various level cities.

Response:

We highly appreciate this great advice. Considering your comment, we have incorporated a new **Section 3.4.3**, which explores the impact of urban scale. Urban scale can be categorized based on several indicators, including economic output, geographical area, and population size. Nevertheless, there is a high degree of correlation among these indicators. For example, cities with robust economic development tend to have larger geographical areas and higher population densities. When it comes to reflecting the impact of air pollution on health, population density has an advantage over economic and area indicators. It can more directly reveal the extent of the harm caused by air pollution to people's health. After careful consideration of all the above factors, we have ultimately decided to use population density as the criterion to differentiate the scale of a city. The population data utilized in this study is sourced from the LandScan Global dataset, which was developed by ORNL. We have incorporated a more comprehensive presentation of the data **in Lines 151-155** of the manuscript. In addition, we have added a description of the urban scale into both the conclusion and the abstract.

3.4.3 The impact of urban scale

The urban scale was categorized according to population density, and comparisons were made between high-density and low-density cities regarding the variations in pollutant concentrations across different functional zones (Figure 10). Specifically, citys with a population density exceeding 510 persons/km² (the 70th percentile) were defined as high-density, whereas those with a density below 151 persons/km² (the 30th percentile) were considered low-density.

The results indicate that cities with high population density exhibit significantly higher concentrations of pollutants compared to those with low population density. In cities with low population density, the improvement in particulate matter ($PM_{2.5}$ and PM_{10}) levels in public management and service zone is minimal. In addition, the reduction of SO_2, NO_2, and CO is more pronounced in residential and commercial zones, while the improvement in transportation zone is the least significant. In cities with high population density, the improvement in $PM_{2.5}$ and SO_2 concentrations in transportation zone is notably smaller compared to other functional zones, at 8.0% and 11.4%, respectively. This can be attributed to the relatively fixed sources of pollutant emissions in transportation zone, particularly in high population density urban areas where traffic flow remains challenging to significantly reduce even with optimized traffic management, thereby posing greater difficulty in achieving improvements (Lopez-Aparicio et al., 2025). Additionally, the high proportion of impervious pavement in transportation zone contributes to the "heat island effect," which hinders the dispersion of pollutants (Yuan et al., 2018). Therefore, future efforts should prioritize pollution control in transportation zone.

From the perspective of different functional zones, the differences of variation in pollutant levels among urban regions with high population density is less pronounced compared to those with low-density (with the exception of SO_2 and O_3). When examining the same functional area across cities of varying population densities, significant differences are observed in public management and service zone, where $PM_{2.5}$ and PM_{10} levels differ by 4.5% and 3.8%, respectively. In contrast, residential zone exhibits minimal variation, with $PM_{2.5}$ and PM_{10} levels differing by only 0.2% and

1.0% (Table S1).

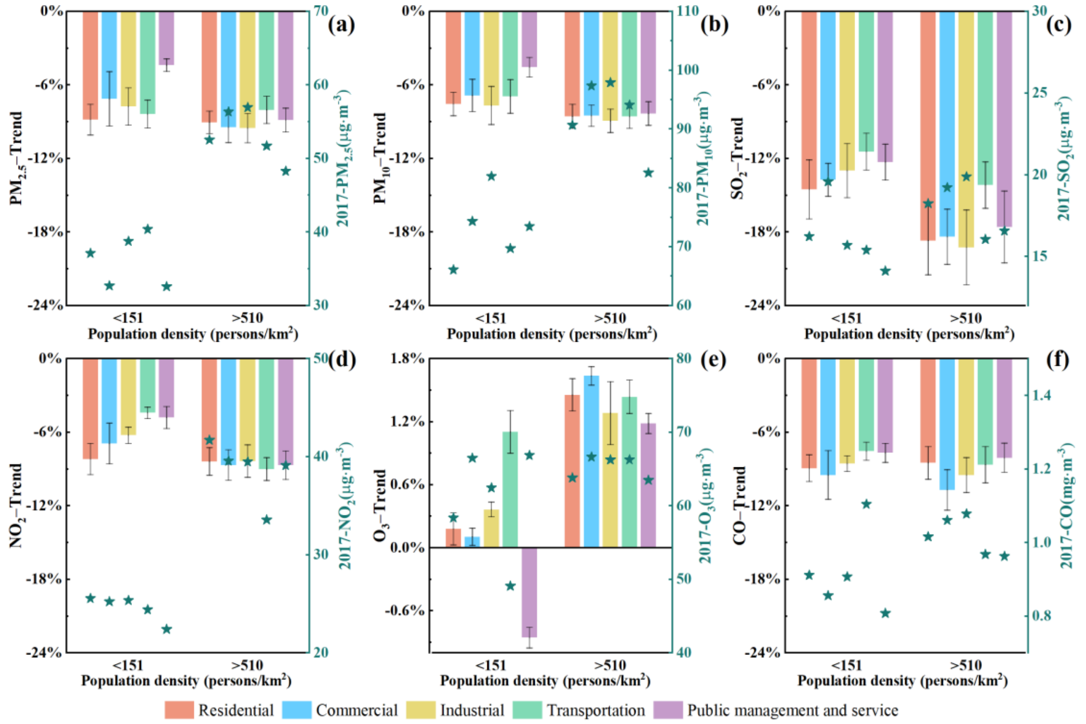

Figure 10. Annual variation trend of $PM_{2.5}$ (a), PM_{10} (b), SO_2 (c), NO_2 (d), O_3 (e), and CO (f) concentrations in various functional zones in different urban scale.

Table S1. Variation differences in pollutant concentrations among different urban scale (low density-high density).

	$PM_{2.5}$	PM_{10}	SO_2	NO_2	O_3	CO
Residential	0.23%	1.01%	4.17%	0.19%	-1.28%	-0.43%
Commercial	2.33%	1.66%	4.65%	1.75%	-1.53%	1.22%
Industrial	1.76%	1.25%	6.26%	2.10%	-0.92%	0.93%
Transportation	-0.33%	1.63%	2.73%	4.59%	-0.33%	1.10%
Public management and service	4.47%	3.77%	5.28%	3.88%	-2.04%	0.39%

Reference

Lopez-Aparicio, S., Grythe, H., Drabicki, A., Chwastek, K., Toboła, K., Górska-Niemas, L., Kierpiec, U., Markelj, M., Strużewska, J., Kud, B., and Sousa Santos, G.: Environmental sustainability of urban expansion: Implications for transport emissions, air pollution, and city growth, Environment International, 196, 109310, https://doi.org/10.1016/j.envint.2025.109310, 2025.

Yuan, M., Huang, Y., Shen, H., and Li, T.: Effects of urban form on haze pollution in China: Spatial regression analysis based on $PM_{2.5}$ remote sensing data, Applied Geography, 98, 215–223, https://doi.org/10.1016/j.apgeog.2018.07.018, 2018.

Comment 10: "These findings indicate that, in the future, the Chinese government should curb ozone pollution, strengthen air pollution control in transportation zone, and formulate more scientific and accurate air pollution control policies based on the local situation of each city." on line 18-21 is not the focus in "Abstract", which doesn't need to be placed here.

Response:

Thanks. We have removed this sentence. Furthermore, in light of the deficiency in specific quantitative data within the abstract, we have incorporated several quantitative metrics to enhance its informativeness.

This study presents a comprehensive spatiotemporal analysis of air quality across various urban functional zones in China from 2017 to 2022, uncovering distinct impacts on air quality due to the unique characteristics of each zone. A general decrease in various pollutant concentrations is observed, a result of stringent pollution control policies. Specifically, the concentration of $PM_{2.5}$ decreased from 46.1 μg/m³ to 30.6 μg/m³. Residential, commercial, and industrial zones show significant declines, whereas the transportation zone experiences the least decrease. However, ozone levels rebound significantly in densely populated residential and commercial zones, and exhibit distinct weekend effects. The research highlights U-shaped seasonal patterns for five key pollutants and inverse seasonal patterns for ozone, which gradually decrease. Furthermore, the daily and seasonal variations of pollutant concentrations in industrial zone are the largest, while those in the public management and service zone are the smallest. For example, the seasonal fluctuation of $PM_{2.5}$ and PM_{10} in industrial zone was 50.5 μg/m³ and 66.1 μg/m³, respectively. Urban scale has the most significant impact on public management and service zone. Notably, spatial heterogeneity is evident, with regional pollutant distributions linked to local emissions, control measures, urban morphology, and climate variability. This study emphasizes the critical link between urbanization and air quality, advocating for continuous monitoring and the development of zone-specific air quality strategies to ensure sustainable urban environments.