Responses to RC2

General Remarks

This study examines the variations of tropospheric aerosols observed by lidar in Wuhan from 2010 to 2024. It presents long-term trends across different periods and explores the respective contributions from natural and anthropogenic aerosol sources. In addition, two case studies are included to illustrate typical pollution events. Overall, while the manuscript is well written and appears to be a good fit for Atmospheric Chemistry and Physics (ACP), I have concerns regarding the scientific novelty and the structural coherence of the paper—specifically, the balance between long-term trend analysis and the inclusion of case studies. These issues should be addressed prior to possible publication. Please find my detailed comments below:

Response: We appreciate the reviewer's thoughtful review and constructive comments. We have added more clarification regarding the motivation of this work and highlighted the importance of the additional four years of observation in the responses, as given below (please see the third paragraph of Section 1). An analysis of meteorological and anthropogenic contributions to the AOD trend over Wuhan during the two stages was added (please see the relevant text to newly-added Figure 6 in Section 3.3) to explain the specific factors that impact the AOD variations. Relevant statements have also been revised to make the logic of the article coherent. All the comments have been addressed accordingly with the modifications in red color in the revised manuscript, and the responses to the individual comments are given in blue color as below.

Specific comments

Comment: How is DOD determined? I would like to see the seasonal variations of DOD in Wuhan. Anthropogenic activities also cause dust emissions and the assumption that DOD is totally natural should be justified.

Response: Thank you for pointing this out. We first divide the lidar-derived backscatter coefficients into the contributions from dust and the non-dust component. (Tesche et al., 2009). By assuming a fixed lidar ratio for dust and non-dust, their respective extinction coefficients can be obtained. Then, DOD can be calculated by integrating the lidar-derived dust extinction coefficient within 0-7 km. The Equations for calculating AOD and DOD have been added in the revised manuscript as follows "**In this study, the tropospheric AOD and dust optical depth (DOD) can be calculated by:**

$$\mathbf{AOD} = \int_{Z_b}^{Z_t} \alpha_p(z)\mathrm{d}z \tag{1}$$

$$\mathbf{DOD} = \int_{Z_b}^{Z_t} \alpha_d(z)\mathrm{d}z \tag{2}$$

where Z_b and Z_t are the lower (base) and upper (top) limits of the integration height, respectively. The Z_b was set to 0 km, extinction coefficients below 0.35 km were assumed equal to that at 0.35 km, possibly causing an uncertainty of <0.05 in AOD (Baars et al., 2017). The Z_t was set to 7 km to ensure a sufficient signal-to-noise ratio (Yin et al., 2021b). The non-dust AOD was derived by subtracting DOD from AOD." (please see lines 92-98)

The seasonal variations of DOD in Wuhan have been analyzed in our previous study (Jing et al., 2024) as follows. "*The largest seasonal average DOD occurs in spring (0.21), followed by winter (0.15) and autumn (0.08). In summer, dust aerosols are rarely observed over Wuhan with a much smaller DOD of 0.02, attributed to the prevalence of the southeastern summer monsoon that inhibits the southeastward transport of dust particles.*" For clarity, we have also added the following sentences regarding the seasonal variations of DOD in the revised manuscript. "**Dust aerosols mainly originate from major desert regions in East Asia, i.e., the GD and TD, and generally intrude into Wuhan during spring (DOD: 0.21) and winter (DOD: 0.15). In summer, however, the prevailing southeastern monsoon suppresses the southeastward transport of dust**

plumes, leading to extremely rare dust intrusions, with a DOD of 0.02, i.e., an order of magnitude lower than in spring (Jing et al., 2024).” (please see lines 241-244)

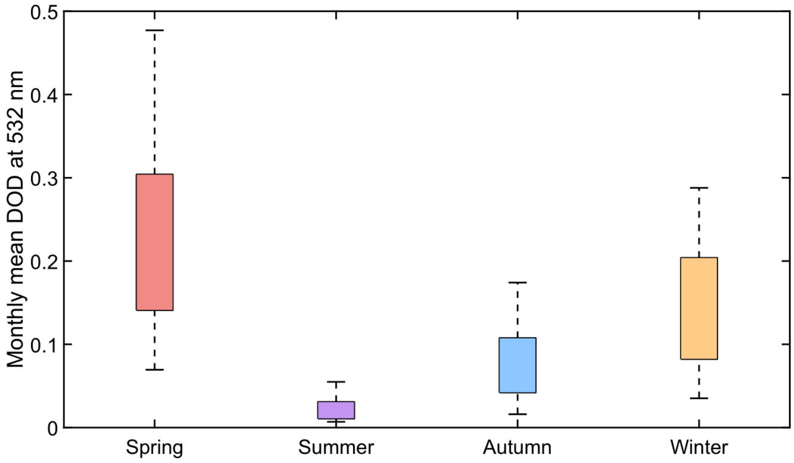

Fig. 6. Box plot of monthly mean DOD in spring, summer, autumn, and winter over Wuhan from October 2010 to June 2020.

Figure 1R. Seasonal variations in DOD over Wuhan during 2010 -2020 (Jing et al., 2024).

Thank you very much for pointing out the potential role of anthropogenic dust. Indeed, our polarization lidar observations alone cannot completely exclude the possible contribution of anthropogenic dust emissions in Wuhan. As a megacity, Wuhan is mainly affected by direct anthropogenic dust from human activities, which differs from indirect anthropogenic dust originating from non-urbanized surfaces such as cropland, pastureland, and dry lakes. Chen et al. (2019) investigated global direct anthropogenic dust emissions and found that the main sources in China are concentrated in the North China Plain, Loess Plateau, and Northeast China, as seen from Figure 2R below. According to their results, we can infer that anthropogenic dust contributions over central China, where Wuhan is located, are nearly negligible. Accordingly, we have added the following statements to the revised manuscript. “**In addition, we cannot completely rule out the potential contribution of anthropogenic dust to the lidar-derived DOD. In a megacity such as Wuhan, direct anthropogenic dust is likely more important than indirect anthropogenic dust emitted from non-urbanized surfaces, e.g., cropland, pastureland, and dry lakes. However, Chen et al. (2019) reported that the major direct anthropogenic dust emissions in China are concentrated in Northern China, while emissions over central China are significantly lower. Therefore, it is reasonable to assume that the lidar-derived DOD primarily reflects contributions from desert dust (i.e., natural sources).**” (please see lines 244-249)

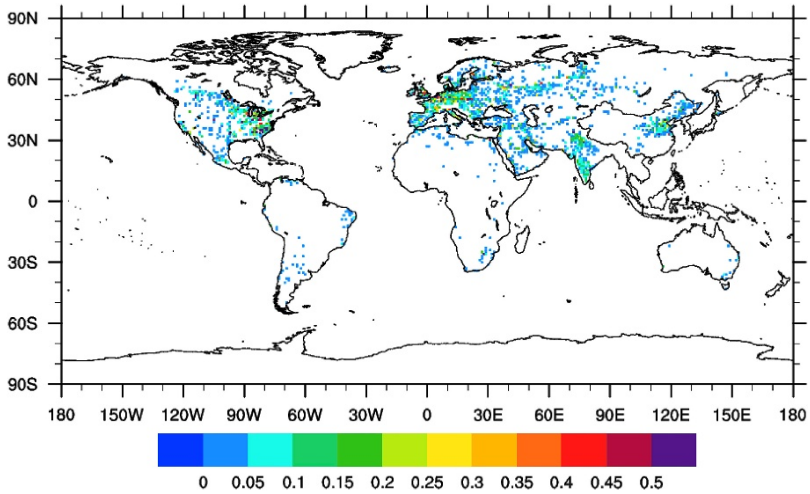

Figure 2R. The spatial distributions of potential direct anthropogenic dust sources at the global scale from 2007 to 2010 (Chen et al., 2019).

Comment: The authors have published a similar paper on 2010-2020 AOD variations over Wuhan and this work is just an extension from their previous study. As such, the scientific motivation of this current analysis is not very clear.

Response: In our previous study, we reported a consistent downward trend in AOD during 2010–2020. However, it can be observed that this AOD decline appeared to cease and even slightly reverse since 2018 (Figure 3R, Yin et al., 2021). Given that the reduction in surface $PM_{2.5}$ concentrations after 2018 has slowed (Geng et al., 2024), it is difficult to conclude whether the consistent downward trend in AOD merely slowed or completely halted at some point after 2018. In addition, in the additional four years following 2020, several factors, including industrial shutdowns due to the COVID-19 pandemic, abnormal Asian dust events, and extreme precipitation, may have influenced AOD levels in Wuhan. Only with these four additional years of lidar observations can we clearly identify a fluctuation period from 2018 to 2024, and further conduct an analysis that can distinguish the respective contributions of meteorological and anthropogenic factors (as presented in the response to the next comment). This presents an important finding that distinguishes the current work from our previous study. For clarity, we have emphasized the abovementioned motivation in the Introduction Section of the revised manuscript. (please see lines 46-53)

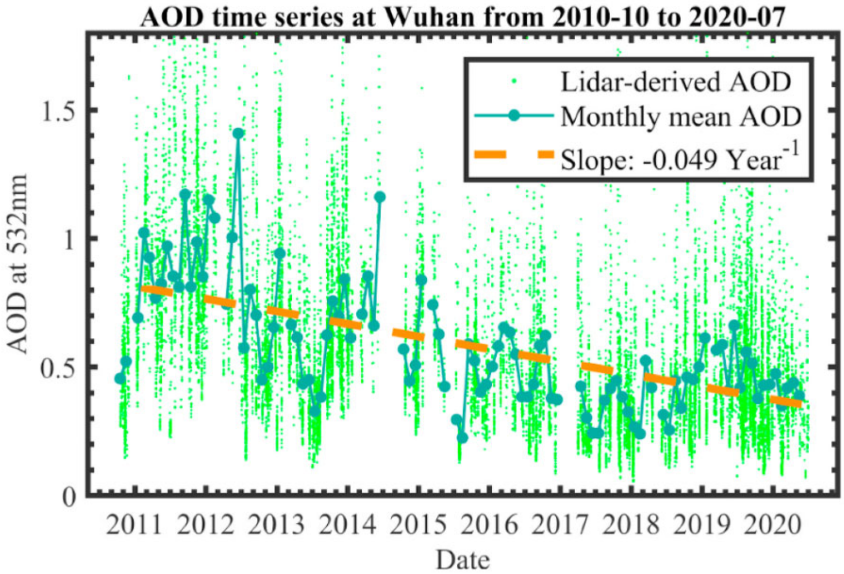

Figure 3R. Variations in 532-nm AOD derived during 2010-2020 (Yin et al., 2021).

Moreover, analyses in this study are based on our first-hand, home-made lidar measurements collected by our team consistently over the past 15 years. As shown in Figure 1, from October 2010 to September 2024, there were 2825 observation days, and a total of 24910 valid cloud-free profiles were obtained from 2139 days, which is 91% and 85% more than 1478 observation days and 1159 days with valid profiles in Yin et al. (2021). In recent years, data coverage has increased substantially, with more than 300 observation days annually (including complete observation records during the initial stage of the COVID-19 lockdown in Wuhan city) and over 250 days yielding valid retrieved profiles of aerosol optical properties. These additional four years of observations provide an important extension to the long-term record of height-resolved aerosol optical properties over central China.

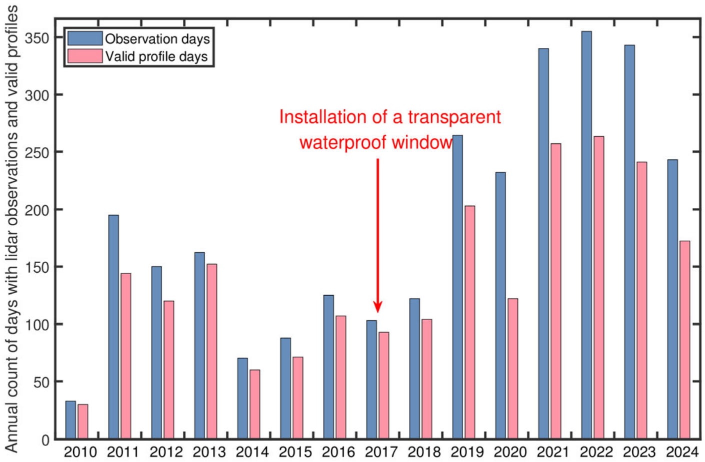

Figure 4R. Annual count of days with lidar observations and valid retrievals of aerosol optical parameter profiles (October 2010 to September 2024).

Comment: More explanations on the AOD trends are needed. Why there was a fluctuating trend in stage II? How to isolate the role of meteorological influence? The driving factors were not well elucidated.

Response: Thank you very much for this constructive comment. We have discussed the DOD variation trend in Section 3.2, which reflects climate change in desert areas. For non-dust AOD variation, we have now added an analysis of the contributions from the meteorological and anthropogenic factors in Section 3.3, applying the Lindeman, Merenda, and Gold (LMG) method from Che et al. (2019). The relative contributions of meteorological or anthropogenic-emission factors to non-dust AOD variation, along with the associated partial correlation analysis, are presented in the newly-added Figure 6 of the revised manuscript. The primary meteorological factors considered include ERA5 hourly relative humidity (%), u- and v-component wind speeds (WS, m s^{-1}) within 1000-850 hPa, total precipitation (Pre, m), vertical velocity (VV, Pa s^{-1}) at 850 hPa, and boundary layer height (BLH, m). Surface-measured $PM_{2.5}$ concentrations were used to reflect the contribution of anthropogenic emissions to non-dust AOD variation. Detailed methodological descriptions have been provided in Section 2.6 of the revised manuscript (please see lines 170-180), and the corresponding analyses have been added to Section 3.3 (please see lines 316-333)

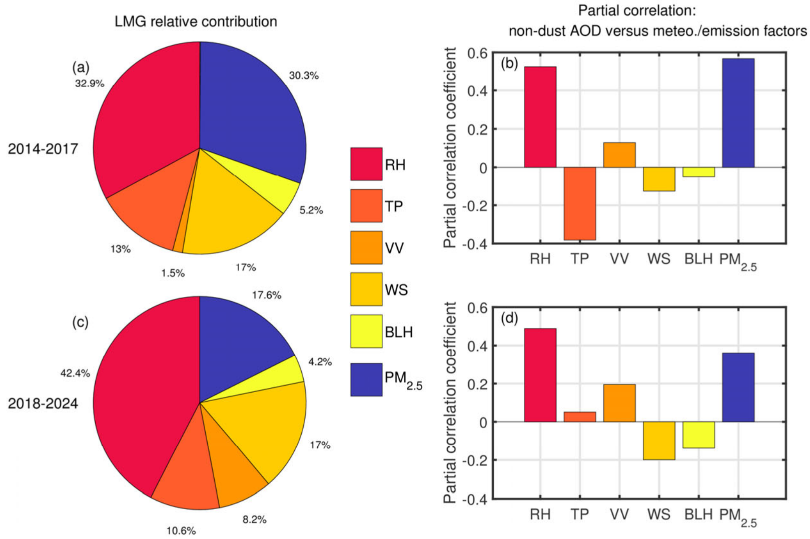

Figure 5R. (Figure 6 in revised manuscript) The LMG method-estimated relative contributions (%) of monthly mean meteorological variations and PM2.5 concentration on monthly mean non-dust AOD during (a) 2014-

2017 and (c) 2018-2024. The partial correlation analyses between non-dust AOD and variations during 2014-2017 and 2018-2024 in Figure 6a (or c) were presented by Figure 6 b and d, respectively.

Comment: In addition, I can't find the linkage between trend analysis and the two case studies. Was aerosol pollution in June 2014 and January 2019 the worst ones? Similar pollution events have been well studied.

Response: These two cases represent typical summer and winter air pollution episodes over central China, frequently observed during our long-term measurements. They correspond to the seasonal variation of anthropogenic aerosols discussed in Section 3.3: enhanced particle extinction coefficient at altitudes of 0.7-2.5 km in summer and below 0.7 km in winter, reflecting transboundary aerosol intrusion and local pollutions, respectively.

The summertime transboundary agricultural biomass burning smoke (ABBS) case in June 2014 shows how smoke from straw burning was transported to Wuhan, resulting in severe air pollution. This event, along with another similar ABBS intrusion event in June 2012 (Zhang et al., 2014), helps explain the enhanced AOD values observed in early summer of the year. Following the implementation of straw-burning bans by the Chinese government, no extreme events with AOD >0.8 have been recorded after 2015.

By presenting the two cases (i.e., one transboundary-driven and the other locally driven), we clearly distinguish and quantify the differential impacts of regional transport and local emissions on AOD under varying conditions. While long-term statistics capture the overall trends, these case studies better reveal the dominant mechanisms behind them. To better link the trend analysis with the two case studies, we have revised the related statements as follows. "**As discussed in Section 3.3, the seasonal characteristics of anthropogenic aerosols show enhanced extinction coefficients at higher altitudes in summer and near the surface in winter. This reflects two typical aerosol pollution patterns: transboundary aerosol intrusion in summer and local pollution in winter**" (please see lines 369-371) and "**Here, we present two typical air pollution cases: summertime transboundary ABBS in June 2014 and wintertime local anthropogenic aerosol pollution in January 2019. These cases provide valuable insights into the dominant mechanisms driving the long-term AOD trends.**" (please see lines 373-375)

References:

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