RC3: 'Comment on egusphere-2025-880', Anonymous Referee #4, 14 June 2025

On behalf of all co-authors, we thank Anonymous Referee #4 for the insightful and extensive comments which certainly contribute to the substantial improvement of the manuscript (MS). Below we respond to each of the general and specific comments which are copied below in black. The general comments consist of two parts which we numbered as GC1 and GC2, where GC1 provides a brief summary of our study and GC2 provides a summary of suggestions which are further elaborated in the specific comments. We have numbered the specific comments as SC1-SC6. After each comment we provide our response, in red, together with changes in the revised MS. Line numbers indicated by L, mentioned by Referee #4, refer to the original MS as published in the ACP discussion section and revisions are quoted with line numbers (indicated by LR) referring to the revised MS.

General Comments

GC1: This manuscript presents an updated analysis of aerosol optical depth (AOD) trends over China from 2010 to 2024, using MODIS/MAIAC C6.1 satellite data and CESM/CAM5 model simulations to distinguish between anthropogenic and meteorological influences. The geographic scope and time span are appropriate, and the study makes effective use of established modeling techniques.

Response to GC1: Thank you for this summary. However, we would like to clarify that the AOD dataset from 2010-2021 in de Leeuw et al. (2023) was MAIAC C6. In this study, the 2010-2021 MAIAC C6 has been replaced with MAIAC C6.1 and then extended until September 2024. This implies that the whole AOD data set is C6.1, hence new data are used which are not merely an extension of the C6 data set used by de Leeuw et al. (2023). In addition, MAIAC C6.1 AOD data differ from C6 AOD data in several aspects (see below). We have reformulated the text to "the C6 time series for 2010-2021 used by de Leeuw et al. (2023) was replaced with the recently released (6 July 2022) MODIS/MAIAC C6.1 data and extended with C6.1 data until September 2024." (LR 142-143). Hence a new data set has been used for the whole study period. MAIAC C6.1 is different from MAIAC C6 (L 139-143), (LR 144-147).

Differences between C6 and C6.1 have been published in papers by Lyapustin and Wang (2022), LPDAAC (2024), Ji et al. (2024), Huang et al. (2024). We briefly describe these differences in Section 2.2. We have also addressed the differences between C6.1 and C6 with a focus on the 5 areas used in our study (until 2024), and in more recent years than used by Li et al. (until 2014) and Huang et al. (until 2021). However, including the analysis of the differences between C6.1 and C6 would render the MS very long and result in the loss of focus. Therefore, we decided to remove this analysis and use the results to prepare a separate paper where we also include validation results using other datasets (SONET), for other years and other areas than Li et al. and Huang et al. We have added a reference to this work "(Fan et al., 2025; in preparation)" (LR 147 in the revised version). An extensive description of these differences is beyond the scope of the current paper, since we do not make specific comparisons with de Leeuw et al (2023), for reasons mentioned in L 135-147).

The validation by Ji et al. (2024) was made over bright surfaces, which are outside our five study areas, and includes data which were mostly collected before our study period. Hence these results have general relevance for the assessment of the accuracy of MAIAC C6.1 AOD data (and therefore this reference is included) but are not relevant for our study. The validation by Huang et al. (2024) includes data in our study areas and overlaps in time (until 2021) with most of our study period. We have included the statistical metrics provided by Huang et al. (2024) in the revised MS and the paragraph now reads: "MAIAC C6.1 has been validated over China by Ji et al. (2024) and Huang et al. (2024). Both studies report that the overall accuracy of the MAIAC AOD products over China is good. The validation by Ji et al. (2024) over bright surfaces, using publicly available reference data from

AERONET and CARSNET until 2014, shows a significant underestimation and negative bias of the MAIAC C6.1 product, which however performs slightly better than DB and C6. The comparison with collocated AERONET AOD data, for the period from 2001 to 2021, by Huang et al. (2024) shows good consistency, with correlation coefficients (R) of 0.933/0.939, root mean square error (RMSE) of 0.152/0.146, bias of 0.005/0.015, mean absolute error (MAE) of 0.094/0.092, relative mean bias (RMB) of 1.221/1.301 and percentage of data points within expected error (EE) of 71.02/68.36. These statistical metrics refer to comparison at the overpass times of the Aqua (13:30 LT) and Terra (10:30 LT) satellites, respectively (Huang et al., 2024, Fig. 2). The comparison shows a slight overestimation of C6.1 at low AOD (<0.5) and a small underestimation at higher AOD." (LR 252-263).

GC2: However, while the extension of the dataset is valuable, the current manuscript lacks scientific rigor in several sections. Most importantly, the paper does not frame its analysis with clearly stated hypotheses or research questions, making it difficult to evaluate the strength of its conclusions. It also fails to provide a rigorous statistical treatment of the data: there is no formal trend analysis, no uncertainty assessment, and no sensitivity testing of model assumptions. These limitations undermine the robustness of the findings and should be addressed in the new version. Additionally, the manuscript would benefit from improved transparency and stronger engagement with regional climate phenomena (e.g., ENSO, East Asian monsoon) which are only superficially mentioned in the discussion.

Response to GC2: GC2 is a summary of comments and suggestions which are further explained in the specific comments SC1 (hypotheses or research questions), SC2 (statistical treatment of the data: there is no formal trend analysis, no uncertainty assessment), SC3 (model assumptions) and SC6 (engagement with regional climate phenomena (e.g., ENSO, East Asian monsoon)). Therefore, we provide our responses to GC2 below each specific comment SC1-SC6.

Specific Comments

SC1: Lack of Hypothesis or Research Questions: the paper would benefit from explicitly stating research hypotheses. Currently, the study lists trends without anchoring them to hypothesis. For example: "Has the relative influence of meteorology increased over time?" or "Does the CESM model successfully replicate observed regional AOD variability under fixed emissions?"

Response to SC1: Thank you for these comments, which made us realize that we should more clearly state the research questions which in the submitted version were hidden in the text (L 148, L 166 and L 163). We have added the following text at the end of the Introduction (LR 173-180). "The objectives of the current study are (1) to investigate the reasons for the flattening of the AOD reduction during 2017-2021, observed by De Leeuw et al. (2023); (2) to investigate what caused the anomalous AOD in the winter of 2014 over the YRD, HNB and PRD, but not over the NCP and SCB (De Leeuw et al., 2023; Fig. 7); (3) to use monthly mean AOD data to accurately identify the start and end of anomalous events, which are hidden in the low-pass filtered data used in De Leeuw et al. (2023); (4) to connect the occurrences of anomalous AOD to specific meteorological conditions and/or anthropogenic interferences; (5) to investigate whether changes in aerosol physicochemical characteristics, in response to emission reduction and climate change, results in different AOD patterns.

Obviously, not all of these questions can be fully addressed in a single study. In the current paper we report and describe the observational data and provide comparisons with the CESM model data (with emissions fixed in 2010). Meteorological and anthropogenic effects on the AOD variations are discussed and possible influences of large scale meteorological effects (El Niño, La Niña, heat waves) and anthropogenic effects (policy measures and economic effects) are indicated. These effects will be discussed in more detail in a follow-up paper. "

These five objectives have been addressed throughout the paper and were discussed ias indicated in the following text added to Section 5: "The objectives stated in the Introduction were addressed throughout this paper. Data presented and discussed show that the flattening of the AOD reduction between 2017 and 2021 suggested by De Leeuw et al. (2023) was a consequence of the offset of AOD reduction by unfavorable meteorological effects (Sections 3.3.1 and 4.3) (Objective 1), as also observed during earlier periods. The anomalous AOD in the winter of 2014 over the YRD, HNB and PRD has been explained by large scale meteorological effects influencing AOD, in particular by ENSO and East Asian winter and summer monsoon (Section 4.2) (Objective 2). Relations between anomalous AOD and meteorological situations have been discussed in Sections 4.2, 4.3 and 4.4 (Objective 4). Changing AOD patterns have been reported and suggested to be due to changing atmospheric composition in response to selective emission reduction policy (Section 4.1), together with the occurrence of anomalous meteorological situations (Section 4.3) (Objective 5). Monthly mean AOD data were used throughout the paper to identify the occurrence of specific events (Objective 3)." (LR 852-863).

As regards the second proposed hypothesis "Does the CESM model successfully replicate observed regional AOD variability under fixed emissions?", this is not a research question because the emissions are fixed in 2010 ("To isolate the effects of meteorology on AOD, anthropogenic emissions were fixed using the monthly values from 2010, which were repeatedly applied to the corresponding months of each subsequent year." (LR 273-274) and therefore cannot be expected to reproduce the AOD variability in an environment where emissions are changing. "However, as discussed in Kang et al. (2019), the CESM results are not representative for actual situations because AOD was simulated using fixed emissions to identify meteorological effects on the AOD. The CMA12 filtered observational and simulated AOD data were normalized for quantitative comparison and to determine anthropogenic and meteorological influences, as explained in de Leeuw et al. (2023)" (L397-401; LR 356-360). The comparisons between (normalized) CESM simulated and observation data are discussed in Section 3.3.1. – 3.3.5.

SC2: Statistical Rigor and Trend Analysis: while normalized CMA12 filtering is used, the paper does not conduct any formal trend tests (e.g., Mann-Kendall, Sen's slope). It is missing the uncertainty assessment, confidence interval, or error propagation. As a result, it is unclear whether observed differences (e.g., 2014 vs. 2018 AOD) are statistically significant.

Response to SC2: Thank you for this comment. Long term trends were determined and discussed in De Leeuw et al. (2023), using rigorously ((KZ(12,3)) filtered AOD time series. The less rigorously filtered data in Fig. 3 of the current MS show that there are many fluctuations and anomalies while in most regions (except NCP) there is no period long enough to justify the determination of a trend. Hence, we have not attempted any trend analysis in the current study where we focus on anomalies and identification of events that may cause them (see also **Response to SC1**).

Having mentioned this, we do notice a general decrease of the AOD in the monthly mean AOD time series (Fig. 2) and more clearly in the CMA(12) filtered time series in Fig.3. We address the decrease in the five regions in the revised version in the Discussion (Section 4.1): "Satellite measurements of AOD over China show that emission reduction policy has been successful in reducing the aerosol concentrations between 2010 and 2018, with an additional but smaller reduction toward the end of the study period, in 2024. Over the NCP, the AOD in 2024 had been reduced to 68% of its value in 2010, over the YRD to 62%, over the PRD to 70%, over the HNB to 55% and over the SCB to 57% (CMA12 values). In 2010 the AOD over the five regions ranged from 0.40 (PRD) to 0.53 (YRD and HNB), while in 2024 the AOD over the five regions ranged from 0.29 to 0.33 (see Figure 3)." (LR 650-655)

As regards uncertainties, we refer to the validation by Ji et al. (2024) and Huang et al. (2024), as well as our own work (Fan et al., in preparation), all versus reference data sets. See our **Response to GC1** for more detail.

SC3: Model Evaluation and Bias Quantification: the CESM model simulations are presented as a basis for attribution to meteorological effects, yet no validation of model performance is provided beyond qualitative agreement. A quantitative comparison between model and satellite AOD (e.g., RMSE, bias, R^2) across regions would strengthen credibility.

Response to SC3: Thank you for this comment. However, as mentioned in the MS, "Model performance on aerosol has been widely evaluated (Lamarque et al., 2012; Fang et al., 2020; Emmons et al., 2010)" (L246-247). In the current study, "To isolate the effects of meteorology on AOD, anthropogenic emissions were fixed using the monthly values from 2010, which were repeatedly applied to the corresponding months of each subsequent year. Meteorological input fields, including horizontal winds, air temperature, surface pressure, land surface temperature, heat fluxes, and wind stresses, were nudged to the MERRA-2 (Modern Era Retrospective analysis for Research and Applications, Version 2) reanalysis dataset (Gelaro et al., 2017; Rienecker et al., 2011) (see also https://rda.ucar.edu/datasets/d313003/; last access 4 March 2024), which provides data at a 3-hour temporal resolution." (LR 273-279). As mentioned in our **Response to SC1**: the model cannot be expected to reproduce the AOD variability in an environment where emissions are changing. "However, as discussed in Kang et al. (2019), the CESM results are not representative for actual situations because AOD was simulated using fixed emissions to identify meteorological effects on the AOD. The CMA12 filtered observational and simulated AOD data were normalized for quantitative comparison and to determine anthropogenic and meteorological influences" (L319-321). The comparisons between (normalized) CESM simulated and observation data are discussed in Sections 3.3.1. – 3.3.5.

SC4: Sensitivity and Robustness Checks Missing: the fixed-emissions approach assumes that changes in modeled AOD are solely due to meteorological variability. However, no sensitivity analyses are provided to test this assumption. Could other fixed assumptions (e.g., emissions inventory resolution, nudging method) bias the attribution?

Response to SC4: Thank you for this comment. Indeed, in our research we followed the fixed-emissions approach, assuming that changes in modeled AOD are solely due to meteorological variability because meteorological parameters are the only ones that change during each month after the first year (2010 in this case) (LR 289-290). This approach is commonly used with different types of models (Ji et al., 2020; Xiao et al., 2021; Zhao et al, 2021; Qi et al., 2022), including CESM / CAMS (Banks et al., 2022) (LR 290-292). CESM / CAMS were also used to determine meteorological effects on AOD (Kang et al., 2019; de Leeuw et al., 2023) and in the current paper we followed up on De Leeuw et al. (2023) but with substantial differences (see our response to SC1), as described in the MS (LR 148-163). None of the publications mentioned above discusses the sensitivity to the resolution of the emission inventory or the nudging method and indeed, also in our study we did not include any sensitivity checks.

Your comment prompted us to consider the possibility of possible biases due to the assumption that all changes are due to variations in meteorological parameters. However, the evaluation of the sensitivity of the model results to the emission inventory resolution or nudging methods applied would be a major task going far beyond the objectives of the current study. In particular because the methods we used are similar to those published in other research papers. However, the questions you raised may have important consequences for the interpretation of our results and those from similar research and may therefore have been addressed in earlier research. In response, we have searched the literature for such effects on aerosol simulations using CESM / CAM but did not find references specifically addressing these topics. However, several papers address nudging and resolution.

As regards nudging, Menut et al. (2024), using WRF Chem, showed that the use of nudging significantly improves the model performances. The importance of nudging for CAM5 was discussed by Zhang et al. (2014) who show the improvement of the top-of-atmosphere radiation budget and cloud ice amount. He et al. (2015) evaluated CESM focusing on the atmospheric component CAM5.1 and concluded that most meteorological and radiative variables are relatively well reproduced with normalized mean biases (NMBs) of 214.1 to 29.7% and 0.7–10.8%, respectively, and mentioned the good performance for liquid water path (LWP) and AOD. In the revised MS we have added "The importance of nudging was discussed in, e.g. Menut et al. (2024), Zhang et al. (2014) and He et al. (2015)." (LR 284-285)

As regards resolution, Bacmeister et al. (2014) demonstrated to some extent that increasing the resolution of the CAM5 model does not necessarily lead to significant improvement in the simulation of long-term variations in meteorological variables. Huang et al. (2016) assessed the recently developed variable-resolution option within the Community Earth System Model (VR-CESM) for long-term regional climate modeling of California, for meteorological variables. Glotfelty et al. (2017) evaluated CESM and concluded that ESM-NCSU provides a reasonable representation of the current atmosphere and that biases in chemical predictions are due to inaccurate emissions, mixing, deposition, and volatility of primary organic aerosol. In the revised MS we have added "This approach is commonly used with different types of models (Ji et al., 2020; Xiao et al., 2021; Zhao et al, 2021; Qi et al., 2022), including CESM / CAM (Banks et al., 2022; Kang et al., 2019; de Leeuw et al., 2023). Model resolution was addressed by, e.g., Bacmeister et al. (2014), Huang et al. (2016) and Glotfelty, et al. (2017). " (LR 290-294)

We also added a reference to model performance "Model performance on aerosol has been widely evaluated (Lamarque et al., 2012; Fang et al., 2020; Emmons et al., 2010; He et al., 2015)" (LR271-272)

References:

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- Banks, A., Kooperman, G. J., & Xu, Y. (2022). Meteorological influences on anthropogenic PM2.5 in future climates: Species level analysis in the Community Earth System Model v2. Earth's Future, 10, e2021EF002298. https://doi.org/10.1029/2021EF002298
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- Glotfelty, T., He, J., Zhang, Y. (2017). Impact of future climate policy scenarios on air quality and aerosol-cloud interactions using an advanced version of CESM/CAM5: Part I. model evaluation for the current decadal simulations, Atmospheric Environment, Volume 152, 2017, Pages 222-239, ISSN 1352-2310, https://doi.org/10.1016/j.atmosenv.2016.12.035.:

SC5: No Integration of Large-Scale Climate Drivers: the paper mentions El Niño/La Niña (e.g., L760) only in the discussion, but these large-scale drivers are not analyzed or incorporated in any statistical way. Given the known influence of ENSO and the East Asian monsoon on AOD, this omission is a missed opportunity for deeper interpretation.

Response to SC5: Thank you for this comment. The influences of El Niño/La Niña and other large scale phenomena on the AOD variations will be discussed in a follow-up paper, to avoid that the current MS becomes too long. We have added this information to Section 4 (Discussion) (LR 641-642; LR 711-727) and Section 5 (Conclusion) (LR 850-851). The influences vary across different regions, depending on weather patterns, large range transport from source regions and geographical effects influencing transport. That is also the reason why different regions were selected across different climate zones as mentioned in Section 2 (L 181-184), with different effects as discussed in the following lines (L185-195) and shown in Fig. 2.

However, to meet concerns expressed by you and Referee#2, we have provided more information on meteorological effects on the AOD evolution in Section 4: "Yin et al. (2017) ascribed the occurrence of severe winter haze events in the North China Plain in 2014 to a weakened East Asian winter monsoon (EAWM) and anticyclonic circulation. Wang and He (2015) ascribed the North China / Severe Summer Drought in 2014 to a weakened East Asian summer monsoon (EASM). A weak EASM results in increased aerosol concentrations over northern China (Feng et al., 2016). Effects of El Niño–Southern Oscillation (ENSO) on air quality in southern China (i.e., south of the Yangtze River) were described by Wang et al. (2022): anticyclonic circulation during El Niño events weakens EASM resulting in low AOD. Vice versa, cyclonic circulation during La Niña events strengthens EASM resulting in high AOD. This may explain the stronger enhancement of the AOD in the PRD, YRD and HNB than in the NCP." (LR 711-719) (Section 4.2). In addition, Section 4.3 describes an analysis where observations and simulations are used to explain differences in aerosol properties and AOD between the periods 2010-2016 and 2018-2024. (LR 728-776).

SC6: Policy Implications Lacking Synthesis: while the abstract references "emission reduction policy," the conclusions do not explicitly synthesize what the results mean for China's air quality regulation or international climate targets. Clarifying how meteorological dominance may affect future policy planning would improve the relevance.

Response to SC6: Thank you for this comment. We have restructured the Discussion in Section 4 and added "Section 4.1 Overall effects of emission reduction policy on aerosol properties" (LR 649-685). We further discuss "AOD reduction over different regions between 2010 and 2018 and influences of anomalous meteorological situations" (Section 4.2) and "AOD variations after 2018 over different regions: increasing importance of meteorological influences" (Section 4.3). Section 5 (Conclusions) summarizes the effectiveness of China's air quality regulations during the study period.

However, the meaning of these results for international climate targets and how meteorological dominance may affect future policy planning is beyond the scope of the current study. The proper evaluation of these effects would require a separate study including future projections using climate scenarios.

Technical Corrections

L248: Clarify whether the "2010 level" refers to monthly averages or annual means.

Thank you for this comment. This has been clarified "anthropogenic emissions were fixed using the monthly values from 2010, which were repeatedly applied to the corresponding months of each subsequent year" (LR 273-274)

L263: Fix punctuation — the sentence ends with a comma.

Thank you for noticing this typo. We have replaced the comma by a full stop.

L322: Explain the method of normalization and its justification; currently unclear.

Thank you for this comment. We have added the following footnote at the first occurrence of "normalization" (LR 161): " Both model and satellite AOD time series were divided by their respective values in July 2010, i.e. at the start of the normalized time series, each of the normalized time series has the value 1, as illustrated in Figs. 5, 7, 9, 11 and 13. If there are no meteorological effects on the AOD, the model data points in the time series are all 1; any deviation from 1 indicates meteorological influences on the AOD. Any deviation between the satellite and model data indicates anthropogenic influences on the AOD."

Figures: Add all missing axis labels; clarify units in captions.

Thank you for this comment. All figures have been checked and axis labels have been added, or corrected. Could you please clarify what you mean with "units in captions"? AOD and normalized AOD are unitless.

Table 1: Consider adding land area or population for context on regional significance.

Thank you for this comment. However, as mentioned on (L184-195), there are large variations in AOD, as well as geographical differences delineating population density and industrialization. There are large regional differences. In De Leeuw et al. (2023) we did add a population density map that showed the variation across each region. In the current study we did not correlate population density, land area and other indicators which may influence AOD and therefore decided to not include this information in Table 1.