**Response to Reviewers**

**Reviewer #1:** “This paper analyzed the application effect of fused satellite AOD products in improving NOx and PM emissions in Northeast Asia. The methods used for the emission constraining suggested in this study seem reasonable, and the difference in results according to the combination of satellite data seems clear. The contents of this paper are expected to be sufficiently meaningful in the field of emissions inverse modeling, so it is judged to be worth publishing in this journal. However, it is believed that revising some of the following matters before publication will help improve the quality of the paper”.

**Authors’ response:** we appreciate your time and concern devoted to reviewing our manuscript. Please find our responses to your comments below:

1. Lines 242-245: There seems to be an insufficient explanation of how you modified the primary PM emission. How did you distribute the AOD concentration to each PM species in Table S2?

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| Authors’ response | Thanks for pointing it out, and we agree that those lines need to be elaborated further. Below is the enhanced explanation for how we distributed the AOD concentration to each PM species in Table S2.  Unlike NO2 in this study (for which reference observations were available owing to TROPOMI), no routine observations have been made until today for the concentrations of individual primary PM species (i.e., those species used in CMAQ’s AOD calculation) in a top-down manner.  Considering such a limitation, we chose the AOD as the reference for adjusting the bottom-up estimates of the primary PM emissions. We computed the sensitivity of the total primary PM emissions (the summation of the emissions of all 19 individual primary PM species) with regard to changes in the AOD; therefore, the resultant adjustment ratio was applied to the emissions of each of the primary PM species “equally”, not in a selective manner (mainly due to the absence of observation references available for those species, and partially for the reason addressed below).  One limitation of our approach above is that the adjustment of the total primary PM emissions does not help us capture the contribution of each individual species to the AOD, which can vary with meteorological conditions (e.g., humidity), aerosol properties (e.g., hygroscopicity, absorbance, and size distribution), and characteristics of emissions sources (e.g., deserts) where the uncertainty in the a priori (emissions) is not negligible. To compute the AOD while maneuvering around rigorous optical calculations devoted for all those drivers, CMAQ (versions earlier than 5.3) employs an empirical approach (Malm et al., 1994; Binkowski et al., 2003) that first lumps the primary PM species into bigger terms of mass concentrations (e.g., sum of light absorbing carbon, sum of organic mass, sum of fine soil, etc.) and then performs an approximation of aerosol extinction coefficients by applying “empirical weights” to those lumped masses, the extents of which have been optimized based on ground-based monitoring network (e.g., IMPROVE sites).  Considering the major aim of our study, we rather focused on shaping a top-down methodology to better exploit the observations afforded by geostationary platforms, than developing more delicate partitioning and weighting techniques beyond inverse modeling, which is worthy as a standalone module development study in the future. |
| Changes in manuscript | * Line 249-254: “To adjust the primary PM emissions, we applied analytical inversion described in Eqs. 2 and 3 to the emissions of 19 primary PM species … the uncertainty of which was set as 100% (Crippa et al., 2019).” * Line 261-264: “In this approach, … no routine observations have been made until today for the loadings of such species over vast areas in East Asia in a top-down manner.” |

1. Section 2.6: Since the distribution (location) of the ground observation sites used for evaluation is not shown, it is difficult to interpret the results, so it would be good to add them to Figure 1. Whether the observation sites are evenly distributed throughout the domain or intensively distributed only in a specific area is very important to the reliability of the evaluation results.

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| Authors’ response | Based on your suggestion, we have updated Figure 1 to depict the distribution of all ground-based in-situ measurement sites used for model evaluation. Some changes, including the locations of AERONET sites, have been made to partially address your next comment below. |
| Changes in manuscript | * Figure 1 and the corresponding caption: “Modeling domain and the locations of the ground-based in-situ measurement sites used for model evaluation.” |

1. Table 1: The constrained emissions based on GOCI-AHI AOD were found to have significantly reduced error compared to that based on AHI AOD (MAM season). What are the causes of this improvement? Figures 2 and 3 show a clear difference between AHI AOD and GOCI-AHI AOD in South China (MAM season) area. Then, was the improvement of NME also seen in the area? First of all, it seems that the distribution of AERONET observation sites used in the evaluation should be illustrated, and the contents should be fully explained based on that.

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| Authors’ response | Thank you for suggesting us a good discussion point. Yes, in MAM 2019, the emissions constrained based on GOCI-AHI AOD more effectively reduced the model bias compared to that based on AHI AOD. This improvement (or the difference in the extent of emissions adjustment) was considered to be originating from whether the high AOD peaks along southeast China (pointed out already in your comment) were captured (Figure 3a) or not (Figure 2a).  Throughout the entire year, the season MAM showed the most frequent occurrences of high AOD peaks over AERONET sites compared to other seasons (Figure 5). Considering the locations of those ground-based sites (see the updated Figure 1 above), many of which cover the southeast China, we first presumed that GOCI-AHI AOD would represent the aerosol loadings more realistically. And then, this was supported by the grid-specific number of AOD records afforded by AHI AOD and GOCI-AHI AOD (Figure 5), the former of which showed noticeably fewer information available for use. Therefore, we concluded that the use of the emissions constrained based on GOCI-AHI AOD, which was considered to better capture the high AOD peaks across the southeast China in a spatiotemporally more frequent and continuous manner, was more effective in resolving the model’s initial AOD underestimation (based on the base emissions). It should also be noted that the emissions adjustment led to an improvement in the model’s performance in terms of normalized mean errors (NMEs) as well, but the extent of improvement was not as noticeable as the improvement shown in NMBs (see the updated Table 1 below). This could be attributed to the fact that NMEs consider both the magnitude and direction of errors, whereas NMBs only consider the direction of errors; even if the magnitude of errors has been reduced, NMEs may not improve noticeably if the direction of errors remains the same.  **Table 1. Summary statistics of the daily mean AERONET AOD (85 sites) and the CMAQ-simulated daily mean AOD before and after the NOx and primary PM emissions adjustments during the study period 2019. (a) The CMAQ-simulated AOD using the base emissions, (b) the CMAQ-simulated AOD using 2019 NOx-constrained emissions, (c) the CMAQ-simulated AOD using 2019 NOx- and PM-constrained emissions using the AHI AOD, and (d) the CMAQ-simulated AOD using 2019 NOx- and PM-constrained emissions using GOCI-AHI fused AOD. R: Pearson’s correlation coefficient; NMB (%): normalized mean bias, NME (%): normalized mean error.**   |  |  |  |  |  |  |  | | --- | --- | --- | --- | --- | --- | --- | |  |  | (a) Base emissions | (b) 2019 NOx-constrained emissions | 2019 NOx- and PM-constrained emissions | | | |  |  | (c) AHI AOD | | (d) GOCI-AHI AOD | | MAM | R | 0.45 | 0.43 | 0.45 | | 0.45 | | NMB | -64.74 | -55.62 | -49.63 | | -26.76 | | NME | 58.24 | 56.56 | 55.91 | | 53.54 | | JJA | R | 0.77 | 0.78 | 0.77 | | 0.77 | | NMB | -29.45 | -19.71 | -9.20 | | 0.21 | | NME | 54.52 | 51.20 | 49.07 | | 48.03 | | SON | R | 0.57 | 0.57 | 0.62 | | 0.62 | | NMB | -51.13 | -47.09 | -38.03 | | -39.70 | | NME | 56.05 | 55.67 | 54.30 | | 55.09 | | DJF | R | 0.55 | 0.48 | 0.57 | | 0.57 | | NMB | -43.23 | -41.77 | -28.65 | | -23.36 | | NME | 68.26 | 67.94 | 66.41 | | 62.90 | | Yearly | R | 0.53 | 0.53 | 0.54 | 0.54 | | | NMB | -50.73 | -42.52 | -33.84 | -19.60 | | | NME | 64.33 | 63.77 | 63.44 | 61.78 | |   Accordingly, we have enhanced the discussions corresponding to the results shown in Table 1 as below. |
| Changes in manuscript | * Lines 440-450: “For example, in MAM 2019, the use of the emissions constrained based on GOCI-AHI AOD more effectively … better capture the high AOD peaks across the southeast China in a spatiotemporally more frequent and continuous manner, was more effective in resolving the model’s initial AOD underestimation.” |

1. Lines 370-374: I know what the author is trying to explain, but these sentences seem to need to be supplemented. Other gas-phase substances, SO2, and NH3 have not been adjusted, so it may be difficult to accurately understand the impact of gas-phase substance emission adjustment. Also, this paper does not accurately define the primary PM emission, so the explanation needs to be more specific.

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| Authors’ response | We agree that those lines need an enhancement. We first updated Table S2 (the name list of the primary PM emissions) to clarify the definitions for the sets of the primary PM emissions (one defined to be the target of the emissions adjustment, and the other measured at the Korean supersites) and corresponding pollutants. And then, we made changes in Table 2 and the lines mentioned above accordingly. |
| Changes in manuscript | * Table S2 and caption: “The list of the primary PM species included the KORUS-AQ emission inventory, and the corresponding pollutants simulated in CMAQ version 5.2 and measured at the Korean supersites.” * Table 2 and caption: “Concentrations (μg/m3) and compositions (%) of surface PM2.5 and its components in Korea … Others: the summation of unknown (undefined) PM2.5 species.” * Lines 404-415: “…the remaining portion (46.74% on average) was mostly comprised of primary PM (36.32% on average) and some unknown (undefined) aerosols (Table 2). As both the contributions of primary and secondary aerosols to aerosol loadings were significant, we considered … that employs more comprehensive sets of top-down constraints (e.g., observational references for SO2 and ammonia loadings in the troposphere).” |

1. The manuscript does not show the accuracy comparison between the constrained results using GEMS-AMI-GOCI2 AOD and GOCI-AHI AOD. Is the reason why this result is not shown because there is no period during which all satellite data exist at the same time? For me, it looks that the adjusted result using GEMS-AMI-GOCI2 AOD shows the highest accuracy. I think the main reason why the GEMS-AMI-GOCI2 AOD showed the best results is the number of AOD records increased in the mixed data. Am I right? And is there any other reason? It would be nice to add a more detailed explanation of the main reason for improved results.

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| Authors’ response | Yes, as you have mentioned above, the use of GEMS-AMI-GOCI-2 AOD seemed most effective in reducing the model bias, and this was considered to be caused by the more information available for use (i.e., the number of AOD records).  To better support this reasoning, it was desirable to either 1) compare the amount of information (i.e., the number of AOD records) afforded by 2022 GEMS AOD (2019 AHI AOD was the proxy of it earlier) versus that afforded by 2022 GEMS-AMI-GOCI-2 AOD (2019 GOCI-AHI AOD was the proxy), or 2) compare those afforded by 2019 GOCI-AHI AOD and 2022 GEMS-AMI-GOCI-2 AOD each other.  Unfortunately, neither approach was available for this study. The 2019 GOCI-AHI AOD product used earlier was served as a prototype for the development of the 2022 GEMS-AMI-GOCI-2 AOD product (the production of the GOCI-AHI AOD product has been discontinued, and it is currently only available for research purposes for the year 2019). Also, the GEMS AOD product and its algorithms are currently on their development stages (2-D rendered products are available for the general public) according to the data provider (NIER). |
| Changes in manuscript | * Lines 463-465: “Note that the GOCI-AHI AOD product used earlier was served as a prototype … discontinued, and it is currently only available for research purposes for the year 2019.” |

**References**

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