PLEASE NOTE

Reviewers' questions are in standard text.

Manuscript text is in *italic*.

Personal communication for reviewer is in **bold**.

Response to reviewer #2:

The authors agreed with reviewer's comment regarding the necessity of the model configurations for WRF and CMAQ simulations, synoptic weather chart in the Asian dust event day, detailed description of in-line dust module in CMAQ v5.0.2, and more clear explanation of the methodology we used for STOPS forecasting. We added a couple of figures and tables, and additional description for them for better understanding, and revised a lot of sentences based on the reviewer's suggestion to reduce redundancy. Also, we revised a couple of confusing and misleading paragraphs in the manuscript with the professional English editing and proof reading to make the manuscript more concise and readable.

Again, the authors responded to most of the reviewer's comments and strengthened our revised manuscript and supplementary document. Please see our responses to the specific comments.

Specific Comments:

1. P3, line 24-35, grammatical errors. For describing what was done in this paper, the past tense would be used. Not just in this paragraph, many grammatical errors are in the text. Sentences are not conveying arguments smoothly that I need to read them a few times to understand authors' intention (such as P3, line 30-33). Sometimes, the wordings are redundant in carrying out the arguments (like p7, p9 line 5-10, p9, line 13-24). With the help of professional English editing and proof reading, the manuscript will be more concise and readable.

The authors revised all of the confusing and misleading paragraphs throughout the manuscript with the professional English editing and proof reading to make the

manuscript more concise and readable.

2. P3, line 11, give citation (Byun and Schere, 2006) when the model is 1st mentioned in the paper.

We added a citation, "Byun and Schere, 2006", in the sentence.

3. P3, line 27, "We utilized STOPS: : :",
P3, line 29, "input data inside the modeling domain."

We corrected the sentences as suggested by the reviewer.

4. P4, line 5, re-phase the sentence to C1 "A small sub-domain of STOPS was configured inside the CMAQ domain and it moves along with the mean wind from CMAQ."

We revised the sentence as the reviewer suggested, and added a figure in the revised manuscript for the better understanding from readers.

<Figure 1 in the revised manuscript>

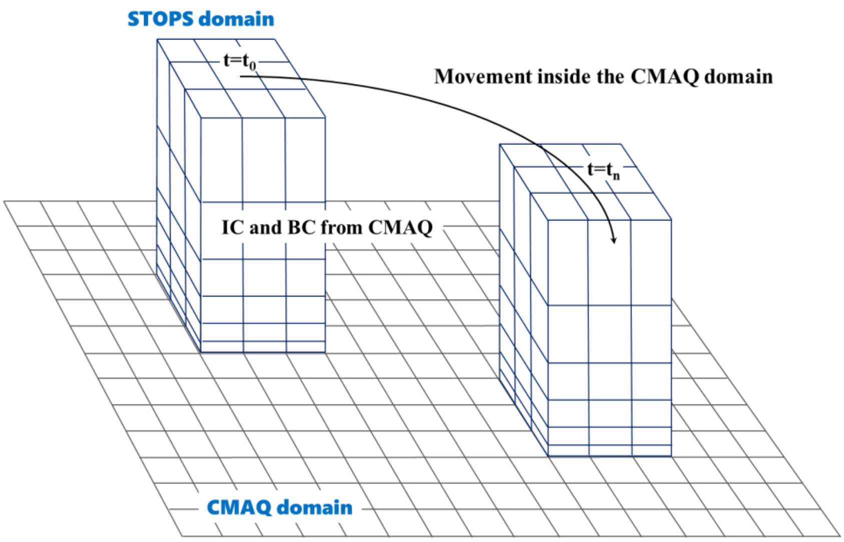

Figure 1. Conceptual diagram showing the basic structure and movement of the STOPS domain inside the CMAQ domain.

5. P4, line 9, the sentence is confusing, please rewrite it.

We re-wrote the sentence to clearly explain how STOPS calculates advection fluxes.

<Section 2.1 in the revised manuscript>

STOPS has the same vertical structure and simulates the same physical and chemical processes as CMAQ, except for the calculation of advection fluxes. CMAQ uses horizontal wind velocity (u and v) from WRF to calculate horizontal advection fluxes, but STOPS calculates the difference between a cell horizontal wind velocity and the mean horizontal velocity in STOPS domain (Czader et al., 2015), so it can consider the moving speed and direction of STOPS domain for the calculation of advection fluxes. Since the STOPS domain moves over time, the horizontal velocity from WRF should be adjusted based on the movement of STOPS domain.

6. P4, line 10-11, ": : :is determined by the layer-averaged wind from the 1st model up to the top of planetary boundary layer (PBL), weighted by the layer thickness.",

P4, line 27, "but in this study, STOPS has been updated to v1.5 and implemented in CMAQ v5.0.2.",

P4, line 31-33, No need to give citation again for the CMAQ. "In this study, we configured the CMAQ model with a domain in a grid resolution of 27 km covering the northeastern part of Asia: : :"

We revised the sentences as the reviewer suggested.

7. P4, line 29, the list and description of all the simulations – standard CMAQ, CMAQ with windblow dust, CMAQ with adjusted emission and four STOPS with adjusted emission are expected in the section titled as experimental design. It can be in its own section if appropriate.

We changed the title of section 2.2 from "*2.2. Modeling system and experimental*

***design*" to "*2.2. Modeling system*" because the section does not include any experimental procedure. We have included the descriptions of each simulation (CMAQ and STOPS) in their relevant sections to better explain the methodology, data and options used for each simulation case.**

8. P5, line 1-2, "Gobi Desert which is a major source of Asian dust."

We corrected the sentence as suggested by the reviewer.

9. P5, line 2, spell out full name of "CB05" and "AERO6" and provide citations.

We added the full names and citations for them in the revised manuscript.

<Section 2.2 in the revised manuscript>

The Carbon Bond chemical mechanism (CB05) (Yarwood et al., 2005) and the AERO6 aerosol module (Nolte et al., 2015) were used for gas-phase and aerosol chemical mechanisms, and initial and boundary conditions were obtained from the standard CMAQ profile.

10. P5, line 5-22, missing CMAQ and WRF's model configuration. Please list physics options used in WRF and the schemes (such as advection, deposition, etc: : :) used in CMAQ. Also, the model configuration for STOPS should be described in this section.

We added model configurations for WRF and CMAQ simulations in the revised supplementary document. Also, we moved section 4.1 (Configuration of STOPS) to this section as the reviewer suggested.

<Table S1 and S2 in the revised supplementary document>

***Table S1**. Configuration and detailed physical options for WRF simulation*

Number of grids	*181 × 143*

Horizontal resolution	*27 km*
Vertical layers	*33 layers*
Initial data	*1°× 1° NCEP Final Operational Global Analysis (FNL)*
Microphysics option	*WSM 3-class simple ice scheme*
Radiation option	*RRTM (long wave) / Dudhia (short wave) scheme*
Surface layer option	*Monin-Obukhov (Janic Eta) scheme*
Land-surface option	*Unified Noah land-surface model*
PBL option	*YSU scheme*
Cumulus option	*Kain-Fritsch (new Eta) scheme*

***Table S2**. Same as Table S1, but for CMAQ*

Meteorology	*WRF*
Number of grids	*174 × 128*
Horizontal resolution	*27 km*
Vertical layers	*15 layers*
Chemical mechanism	*CB05 (gas-phase) / AERO6 (aerosol)*
Chemical solver	*Smvgear*
Horizontal advection	*Yamo*
Horizontal diffusion	*Multiscale*
Vertical advection	*WRF*
Vertical diffusion	*ACM2*
Deposition	*M3dry*
Anthropogenic emissions	*MIX-2010 / CAPSS 2011*
Dust emission model	*In-line windblown dust model*

11. P5, line 24, please provide overview of the synoptic weather pattern during the dust event that will help readers to interpret the model result.

We added two synoptic weather charts in the revised supplementary document to show the synoptic weather pattern on the first day of the Asian dust event (22 February, 2015), which resulted in the transport of massive dust from Mongolia region to the Korean Peninsula.

<Figure S1 in the revised supplementary document>

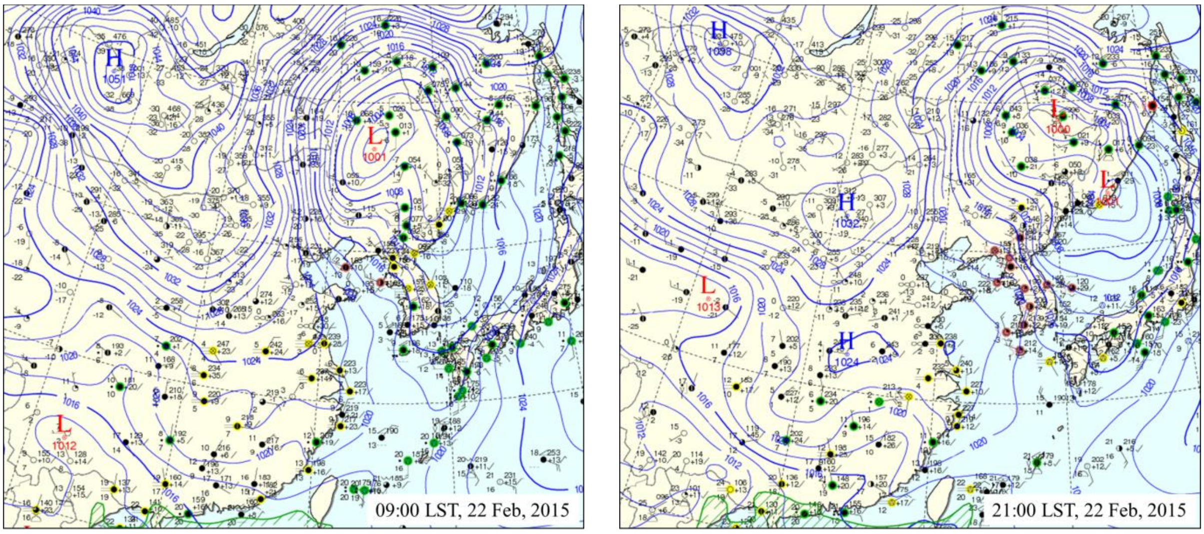

Figure S1. *Surface-level synoptic weather chart near the Korean Peninsula on 22 February in 2015, which is the first day of the Asian dust event in this study.*

<Section 2.2 in the revised manuscript>

During the event days, massive dust over the GOBI desert and Mongolia region was transported to the Korean Peninsula. This happened due to the southeastward wind resulting from high pressure over the Mongolia region and low pressure over the northeastern part of China (Fig. S1 in the supplementary document).

12. P5, line 23-25, the paragraph should be re-written to give clear information about the simulation period and when the dust event happened. “The WRF-CMAQ simulations were conducted for the period of January 21st – February 28th, 2015 which included the first ten days for spin-up. Evaluations applied to the month of February, 2015 and the three-day Asian dust event occurred during February 22nd – 24th. The PM surface observations measured at

the surface stations in Korea are listed in Table 1.

We re-wrote the paragraph as the reviewer's suggested.

13. P5, line 29, "This study used surface observational data: : :"

We revised the sentence as suggested by the reviewer.

14. P6, line 3, what does it mean for constraining of PM concentration? Is it through data assimilation? If so, it should be described in methodology section like 2.2.

We did not use data assimilation technique for constraining PM concentration in forecasting. Usually, the data assimilation techniques are computationally more expensive than the simplified constraining approach. As described in section 4.1 in the revised manuscript, we regarded the GOCI-derived AOD as a surrogate for PM emissions and hence indirectly constrained the original PM concentrations by using the alternative emissions. The GOCI-derived AOD was converted to emission unit and the converted emission values were used for the STOPS forecasting. Section 4.1 in the revised manuscript contains more detailed description for the method we used for STOPS forecasting with GOCI-derived AOD.

15. P6, line 30-35, what does the windblown dust module do in CMAQ? Any references for other studies using it? Figure 2 comparison shows almost no difference in PM predictions from simulations of standard CMAQ and CMAQ with dust module, even during the period of the dust event. If you lower the C2 threshold in the dust module, will the CMAQ be able to simulate the dust event?

We provided a brief description of the CMAQ in-line windblown dust module and a reference for it in section 3.1 in the revised manuscript.

<Section 3.1 in the revised manuscript>

The module calculates the vertical dust emission flux (F) by following formula described by

Fu et al. (2014).

$$F = \sum_{i=1}^{M}\sum_{j=1}^{N} K \times A \times \frac{\rho}{g} \times S_i \times SEP \times u_* \times ({u_*}^2 - {u_{*_{ti,j}}}^2)$$

where i and j represent the type of erodible land and soil, K is the ratio between vertical and horizontal flux, A is the particle supply limitation, ρ *is the air density, g is the gravitational constant,* S_i *is the area of the dust source,* SEP *is the soil erodible potential,* u_* *is the friction velocity, and* $u_{*_{ti,j}}$ *denotes the threshold friction velocity.*

When we used the threshold values suggested by Fu et al. (2014), which are lower than standard ones, the simulated PM_{10} concentrations over China, particularly in areas adjacent to the Gobi Desert and its downwind side increased as demonstrated by Fu et al. (2014). But the increase in Korea was relatively minimal and the result did not show reasonable agreement with observation. In this study, the average value of the simulated two-meter temperature during the period was 274.87 K, which was significantly lower than that founded by Fu et al. (2014) (286.30 K). The low friction velocity values below the threshold came from the cold weather conditions over the East Asia during the simulation period. We concluded that the employment of the in-line windblown dust module in CMAQ simulations did not provide discernible enhancement in PM_{10} concentrations because of lower friction velocity than the threshold in the module. These are the reason why we thought a new modeling frame work for the prediction of Asian dust event.

16. P7, line 4-20, I think it will be more appropriate to have these paragraphs in section 2.3 to describe how the satellite AOD used for CMAQ evaluations. Then, section 3.2 can focus on presenting the comparison and discussing the underestimation during the dust period.

As suggested the reviewer, we moved the paragraphs in section 3.2 to section 2.3 in the revised manuscript, so section 3.2 can focus on presenting the comparison and discussing the underestimation during the dust period.

17. P8, section 4.1, it is out of place but better to be moved to section 2.2.

We moved section 4.1 (in the previous manuscript) to section 2.2 (in the revised manuscript) as the reviewer suggested.

18. P8, line 32, why the STOPS domain does not cover the whole Korean Peninsula? In this case, is the AQMS station at the east coast not included in the domain?

We found a problem with the initial position of the STOPS domain. The location of domain center was not 40° N, 119° E, but 40° N, 121° E, so we corrected relevant parts in the revised manuscript (Figure 2 and 10).

19. P9, section 4.2, I cannot get the point of the section. Using half of the page, it repeats findings (CMAQ failed to simulation the dust event and STOPS could produce CMAQ's result with mush less computational time) that have already shown in the previous sections. This section should be re-written to be more concise and informative.

We re-wrote section 4 in the revised manuscript to better explain the method we used for a new PM forecasting using STOPS. We added a figure, which briefly describes entire procedures of the PM forecasting using STOPS with GOCI-derived AOD data.

<Figure S3 in the revised supplementary document>

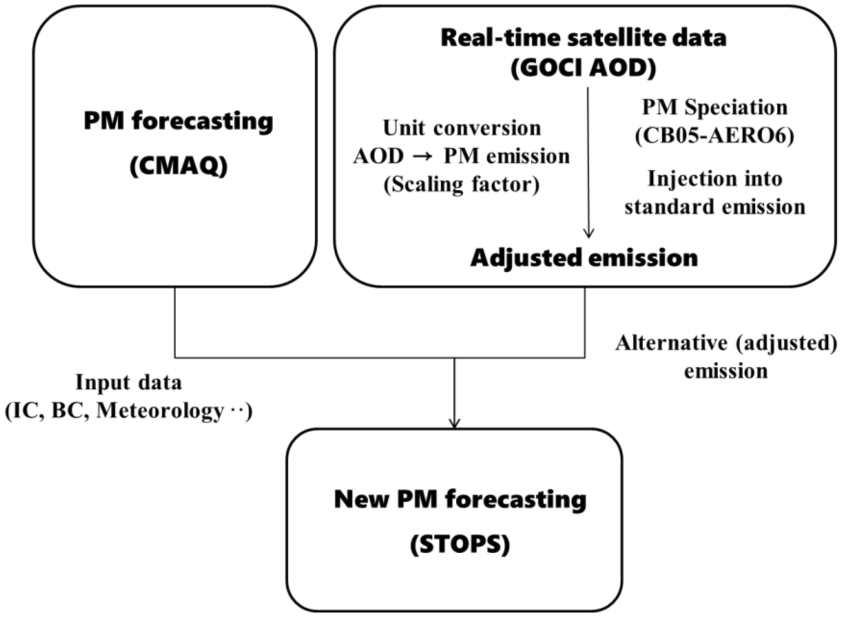

Figure S3. *Schematic flowchart describing the procedure of the new PM forecasting by STOPS using the real-time AOD data from GOCI.*

20. P9, line 34, I cannot understand how can you add extra amount of PM directly to CMAQ without some kind of data assimilation technique?

Please see our response for question 14.

21. P10, Rather than improving the dust module in CMAQ, using satellite AOD to take into account the extra emission due to the dust event is one reasonable way to improve PM10 prediction for this study. But why the STOPS model is a tool for "a more accurate prediction" (as highlighted in the title)? STOPS is more efficient computationally than running the full CMAQ model? The improvement shown in STOPS results is due to the use of adjusted emission estimated according to the satellite data. By using the same adjust emission, can the CMAQ also produce better PM10 prediction compared to the standard CMAQ?

As the reviewer addressed, the significant improvement in the simulated PM_{10} was contributed by constrained PM concentrations based on GOCI AOD. Even though we used CMAQ instead of STOPS, it would produce the similar results as in STOPS. However, this study assumes a real forecasting situation. In the case of the massive dust transport is captured by satellite measurement, the current forecasting results should be

replaced in a very short time period before the dust storm reaches the receptor regions (Korea in this study). A new forecasting using CMAQ with GOCI AOD cannot be done within a few minutes. Thus, the computational efficiency of STOPS is the most important benefit, which allows the near real-time update of PM forecasting results.

As the reviewer suggested, we revised a couple of misleading sentences throughout the manuscript by saying that STOPS itself does not improve any air quality prediction, but help for "quicker" forecasting.

22. P10, line 32, what is PMT?

The PMT is the same as $PMT_{i,j}$, the estimated emission rate of total PM in each grid cell. We changed PMT to $PMT_{i,j}$ for the better understanding from readers.

23. P11, line 8-16, the text talks about the CMAQ .vs. STOPS simulations but the figure is in CMAQ domains. And the caption indicates both are CMAQ simulations. Please clarify and use consistent names.

We changed Figure 8 in the revised manuscript to show PM_{10} concentrations inside the STOPS domain, and revised its caption for clear description.

<Figure 8 in the revised manuscript>

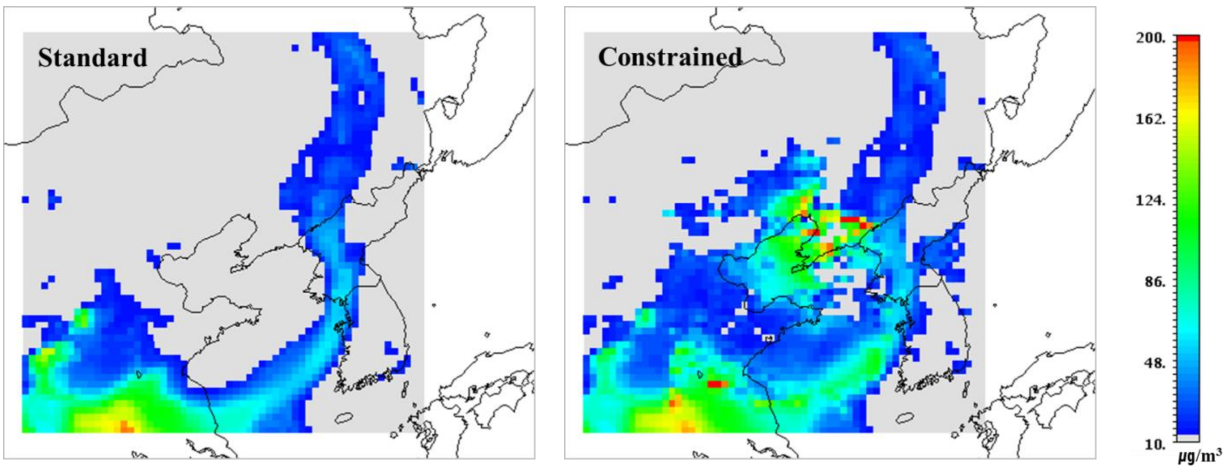

Figure 8. *Difference of the simulated PM_{10} concentrations ($\mu g\ m^{-3}$) between the standard CMAQ run (left) and STOPS forecasting run with alternative emission estimated according to*

GOCI-derived AOD (right) inside the STOPS domain at 12:00 LST on 22 February in 2015.

24. P11, line 8, re-phase it to "Figure 7 shows the comparison of the PM10 concentration from CMAQ simulations using standard and adjusted emission".

P11, line 33-37, I do not know what the "updated" is referring to. Use just "STOPS simulation" instead of "updated STOPS simulation"

P12, line 6-7, re-phase to "the impact of the alternative emissions on the PM10 prediction highly depends on the durations of emission release and the impact was gone after the release ended."

P12, line 17, ': : :AOD data contained missing data due to the cloud cover over the C3 study area : : :"

P13, line 28-29, re-phase to "With reasonable meteorological input, the under-prediction of PM10 concentration was mainly due to the inaccurate estimation of dust emission during this period used in CMAQ."

Thanks. We revised the sentences as the reviewer suggested.

25. Figure 2, the CMAQ_dust simulation should be explained in the text and please briefly describe what is the dust module in CMAQ.

We provided a brief description of the CMAQ in-line windblown dust module and a citation for it in section 3.1 in the revised manuscript. Please see our response for question 15.

26. Figure 7, caption: ": : :alternative emission estimated according to the GOCIderived AOD."

As the reviewer suggested, we corrected the caption for Figure 8 in the revised manuscript.