Dear ACP Editor:

We have addressed all the comments raised by both reviewers, and incorporated them in the revised manuscript. Please find below our itemized responses to the reviewer's comments.

Thank you very much for your consideration.

Sincerely,
Yang Yang, et al.

COMMENTS TO THE AUTHOR(S)

Impacts of aerosol-radiation interaction on meteorological forecast over northern China by offline coupling the WRF-Chem simulated AOD into WRF: a case study during a heavy pollution event
Manuscript ID: acp-2019-1056
Authors: Yang, et al.

Reviewer 1

General summary

This paper assesses the impact of incorporating aerosol-radiation interactions in the NWP models on surface radiation and weather forecasts during a heavy pollution episode in North China Plain. Hourly AOD fields simulated using WRF-Chem model are fed offline into the radiation schemes of a WRF based NWP system called RMAPS-RT. The inclusion of aerosols in the NWP system reduced overestimation of daytime surface radiation magnitude and budget, and improved forecasts of temperature and wind speed. The results highlight the importance of including aerosols in the NWP system and are interesting. However, the paper lacks detailed evaluation of AOD and PM2.5 (see my specific comments on improving the evaluation part). Additionally, the paper does not discuss whether or not aerosol induced changes in the weather forecast are statistically significant or not. If changes are not statically significant, it may not be worthwhile to incorporate more realistic aerosol information in the NWP models and

just a climatological aerosol representation in the radiation routines may be sufficient. Thus, I recommend major revisions of the paper before publication in ACP.

Response:

We really appreciate the valuable comments. We have made the following changes according to these comments.

More detailed evaluation of simulated AOD against MODIS and CALIPSO satellite-based products were performed and added in the revised manuscript. In addition, we added more quantitative evaluations of $PM_{2.5}$ mass concentrations including spatial distributions of bias, root mean square error, and correlation coefficient for individual sites during pollution and relatively cleaner periods, as well as the time series of hourly averaged observed and simulated $PM_{2.5}$ concentrations over the Henan and Hebei provinces.

To address the issue about the statistically significance of the aerosol induced impacts on weather forecast, we further conducted three sets of 24-hour forecasts for a longer period lasting 27 days (Jan. 13th- Feb. 8th, 2017), with no AOD field (NoAero), climatological AOD fields (ClimAero) and WRF-Chem simulated hourly AOD fields (ChemAero) included, respectively. The results indicated that the simulation with the inclusion of WRF-Chem simulated hourly AOD fields outperformed other two simulations and showed more improvement on the forecast of surface temperature and near surface wind speed than the simulation with climatological AOD fields. These results are in consistent with the conclusions in the current study. Please see more detailed discussion below.

We expect that you will find that your comments have been considered fully and properly in our revised manuscript. Below are our item-by-item responses.

Specific comments

Line 123: change “accessed” to “assessed”.

Response:

Thanks, corrected.

Line 195-196: why RRTMG was not used for WRF-Chem simulations. Are aerosol-radiation interactions turned off purposely in the WRF-Chem simulations?

Response:

Thanks for your insightful comment. The RRTMG scheme was not included in the version 3.3.1 of WRF-Chem, which was applied in the current study and also in our operational system. The aerosol-radiation interactions were turned off in the WRF-Chem simulations. We do understand that the aerosol-radiation interactions could benefit the simulation of $PM_{2.5}$, particularly the peak values. We would include the aerosol-radiation interactions of WRF-Chem in online test in our further research.

Line 203: Why FNL data were used in WRF-Chem experiments and ECMWF data used as met IC/BC in WRF forecast? What is the sensitivity of meteorological parameters to different driving datasets?

Response:

Thanks for your comment. The ECMWF forecast data were adopted as meteorological IC/BC in the operational meteorological forecast system based on WRF, and the meteorological field forecasted by WRF with the inclusion of data assimilation were then input as IC/BC of operational WRF-Chem simulation. In the beginning of the current study, we first tried FNL data for meteorological IC/BC of WRF-Chem forecast and found that the results were reasonable and satisfying, so we did not evaluate the sensitivity of meteorological driving datasets further. According to the colleagues in our Development Testbed Center, the direction of the WRF forecast meteorological parameter biases (e.g. overestimated temperature) are not so sensitive to the initial conditions, as the same direction of biases occur quickly even with assimilated initials that intentionally overcorrect the original biases; thus we assumed the system is more sensitive to certain processes instead of initials in current configurations. We will conduct further detailed research and test about the sensitivity of meteorological parameters to different driving datasets in our future research.

Lines 205-206: Did you run WRF-Chem continuously for 10 days? If yes, did you use any kind of nudging to limit the drift of meteorological fields from the large-scale reanalysis fields?

Response:

Thanks for your comment. We tried without nudging over the plain areas of northern China during wintertime in our previous study, and found that the simulations of pollutant were reasonable and the drift were acceptable. Thus, we run WRF-Chem continuously for 10 days without nudging in the current study.

Lines 213-214: I do not agree that MODIS AOD retrievals are not available during this episode. I did a quick average AOD plot in Giovanni and the resulting images are shown below in Figures R1 and R2 for both MODIS Terra and Aqua satellites. While AOD is not available everywhere in the domain but I think the datasets is still useful for validation of the model simulated spatial distribution of AOD. I encourage the authors to use Level 2 MODIS AOD retrievals for comparison with WRF-Chem.

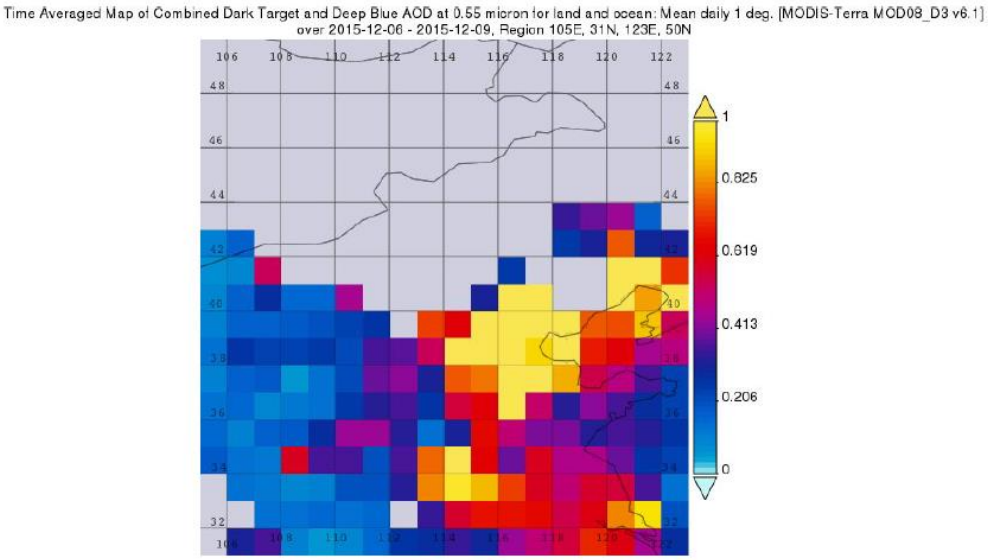

Figure R1: Time averaged MODIS Terra AOD map for 6-9 December 2015.

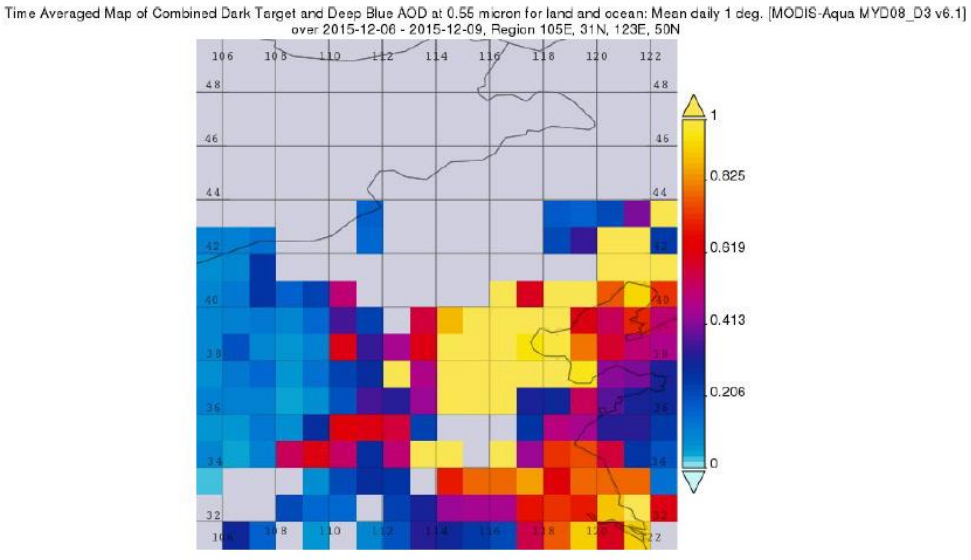

Figure R2: Time averaged MODIS Aqua AOD map for 6-9 December 2015.

Response:

Thanks for your helpful and insightful comment. According to your suggestion, we evaluated the simulated AOD with MODIS Terra and Aqua (Fig. S1). It was seen that WRF-Chem is capable to capture the AOD spatial distribution and also reproduced the

transport paths during the event. The simulated high-valued AOD located in Henan on Dec. 6th, then the center moved to Hebei and Beijing on 7th and shifted to northeast areas afterwards. The variations of simulated AOD were in consistent with both Terra and Aqua with slightly overestimated peak value of AOD. In particular, the simulated shifting of AOD center to northeast areas was also observed in Aqua (Fig. S1r-s). We have added the Fig. S1 and the discussion in the revised manuscript (around L247-L255).

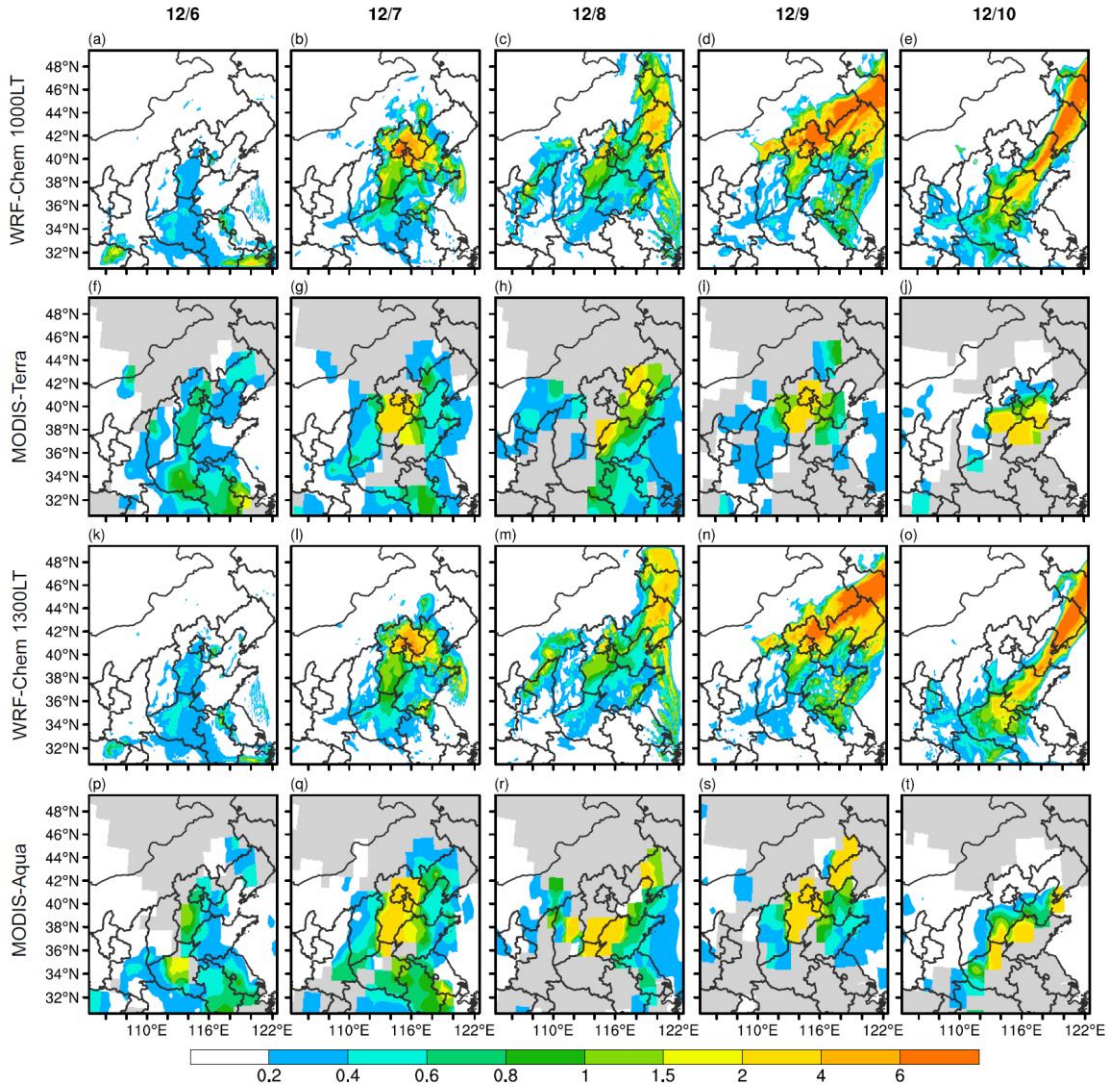

Fig. S1 The WRF-Chem simulated and MODIS observed spatial distribution of AOD on 6th-10th December (from left to right). The first (a-e) and third rows (k-o) are WRF-Chem simulations at 1000LT and 1300LT (MODIS path times) respectively. The second (f-j) and fourth (p-t) rows are MODIS Terra and Aqua observations, respectively. Gray areas in (f-j) and (p-t) denote the missing values.

Lines 249-250: In addition to my above comment, the authors should consider using other satellite-based products such as MISR and MAIAC AOD, and aerosol extinction coefficient retrievals from CALIPSO.

Response:

Thanks for your helpful and insightful comment. According to your suggestion, we have compared the modeled 550nm aerosol extinction coefficient with CALIPSO, and displayed AOD from MISR level 3 daily product.

Fig. S2 displayed the vertical distribution of simulated 550nm aerosol extinction coefficient compared to those from CALIPSO. Four cross sections along CALIPSO paths on 6^{th} to 9^{th} December were shown. The results indicated that the model could generally reproduce the vertical distribution of extinction coefficients at 550nm in terms of comparable magnitude with those from CALIPSO, particularly on 6^{th}, 7^{th} and 9^{th}, December. However, CALIPSO showed more high values at lower altitude (below 1km) that model failed to capture; the inconsistency may be associated with both CALIPSO retrieval uncertainties at the low altitude and the model itself. We have added the Fig. S2 and the discussion in the revised manuscript (around L255 – L264).

Fig.S3 showed the spatial distribution of AOD at 555nm during 6^{th} to 10^{th} December obtained from MISR. It was seen that the valid fields of AOD from MISR are quite limited during this polluted episode. Therefore, we evaluated the simulation of AOD against MODIS AOD (as discussed earlier) rather than MISR.

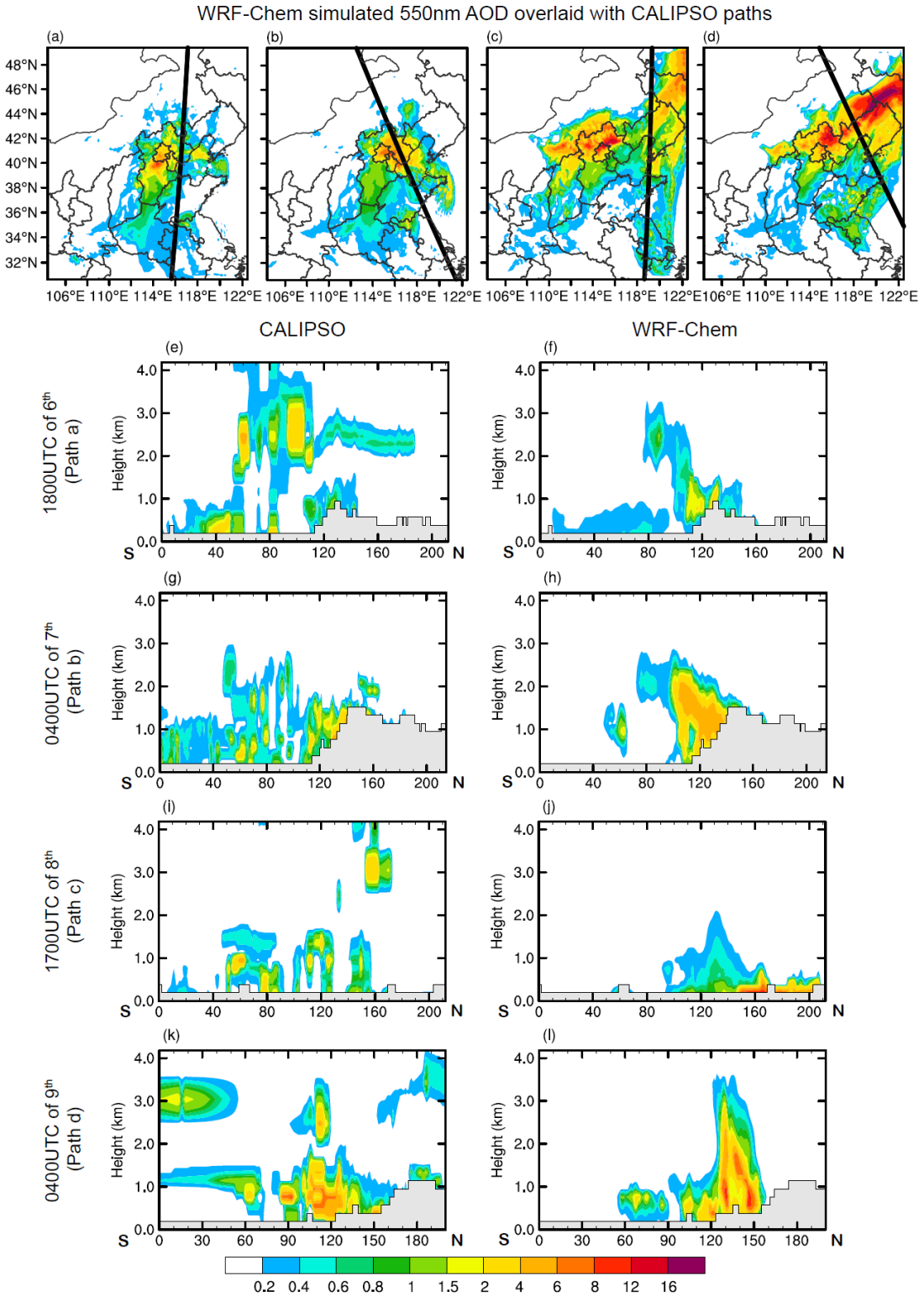

Fig. S2 The WRF-Chem simulated 550nm AOD (shadings) on (a)1800UTC of 6th, (b) 0400UTC of 7th, (c)1700UTC of 8th, (d) 0400UTC of 9th December overlaid with CALIPSO paths (black thick solid). (e-l) denote the corresponding vertical distributions of aerosol extinction coefficient at 550nm from (e, g, i, k) CALIPSO and (f, h, j, l) model simulations. Gray areas in (e-l) denote the terrain.

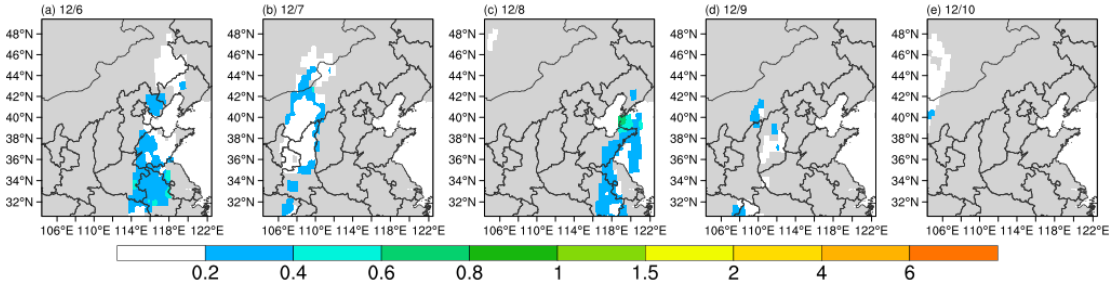

Fig. S3 The spatial distribution of AOD at 555nm from MISR on (a) 6th, (b) 7th, (c) 8th, (d) 9th and (e) 10th December respectively, the gray areas indicate the missing values.

Figure 3 and Lines 253-259: This discussion is very qualitative and I recommend the authors to include some quantitative information about the evaluations. I suggest plotting time series of hourly averaged observed and modeled PM2.5 mass concentrations over the Henen and Hebei provinces (similar to Fig. 4 for the three cities). Maps of bias, root mean square error, and correlation coefficient for each site for the heavy pollution and cleaner periods will also be useful to understand model skill in reproducing the heavy pollution event.

Response:

Thanks for your helpful suggestions. We have added the spatial distributions of bias, root mean square error, and correlation coefficient for individual site during the heavy pollution and relatively cleaner periods (Fig. S4), and the time series of hourly averaged observed and modeled $PM_{2.5}$ mass concentrations over the Henan and Hebei provinces (Fig. 5 d-e).

Figure S4 displayed the mean bias, root mean square error (RMSE), and correlation coefficient during the heavy pollution and relatively cleaner periods. It was seen that the biases of $PM_{2.5}$ were generally less than 40 μg m^{-3} with the correlation coefficient exceeding 0.8 during clean period (Fig. S4a-c). Compared with clean period, the bias and RMSE were generally larger during polluted period (Fig. S4d-f). The $PM_{2.5}$ concentrations over most areas of the domain were underestimated with the maximum bias exceeding 160 μg m^{-3}. Overall, the correlation coefficient was generally higher than 0.4 in northern China during the polluted period, particularly over Beijing with the correlation coefficient reaching 0.8.

To further assess the temporal evolutions of the pollution, the simulated $PM_{2.5}$ concentrations at three major cities (Beijing, Shijiazhuang and Tianjin) and two provinces (Hebei and Henan) in northern China were compared with observation as shown in Fig. S5. It showed that the hourly variations of $PM_{2.5}$ concentration, including

the occurrence of several high peaks at the three cities, as well as the gradual accumulation of pollution in Hebei and Henan could be reasonably reproduced by WRF-Chem. The correlation coefficients (R) between simulation and observation at Beijing, Shijiazhuang, Tianjin, Hebei and Henan were 0.85, 0.89, 0.76, 0.92 and 0.77 respectively. It should be noted that there exits slight overestimation (underestimation) of the peak magnitude during 9th to 10th at Beijing and Shijiazhuang (Tianjin, Hebei and Henan); the overestimation in Beijing and Shijiazhuang is possibly associated with the frequent emission changes caused by emission-control-measures in reality which are not dynamically updated in the model; the underestimation is more related with the deficiency of model skills, such as missing heterogeneous reaction paths in the chemistry scheme.

We have added Fig. S4-5 and the corresponding statement in the revised manuscript around L284-L293 and L294-L308.

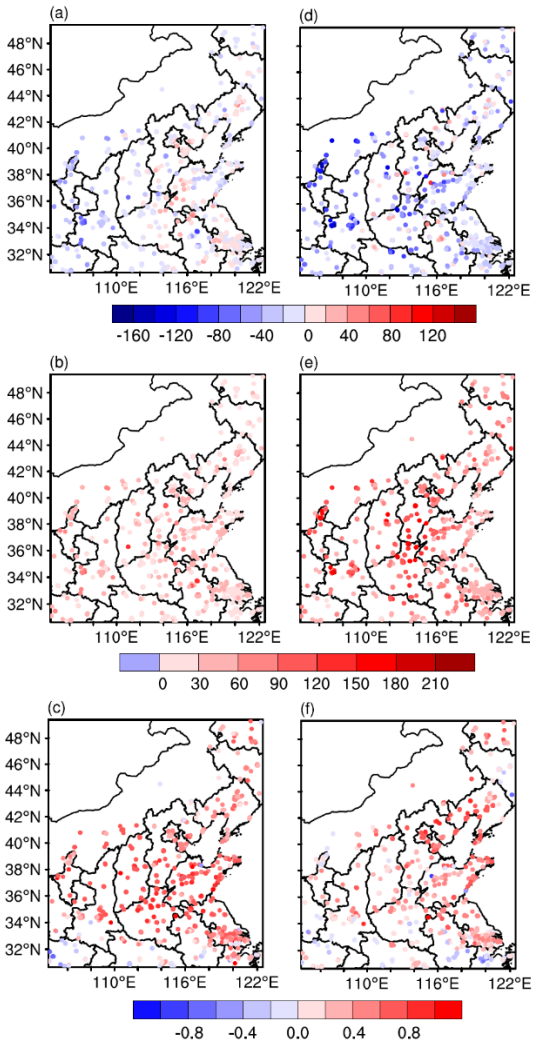

Fig. S4. The (a, d) bias (μg m^{-3}), (b, e) RMSE (μg m^{-3}), and (c, f) correlation coefficient (1) averaged (a-c) during clean period (3th to 5th Dec) and (d-f) the polluted period (6th to 10th Dec).

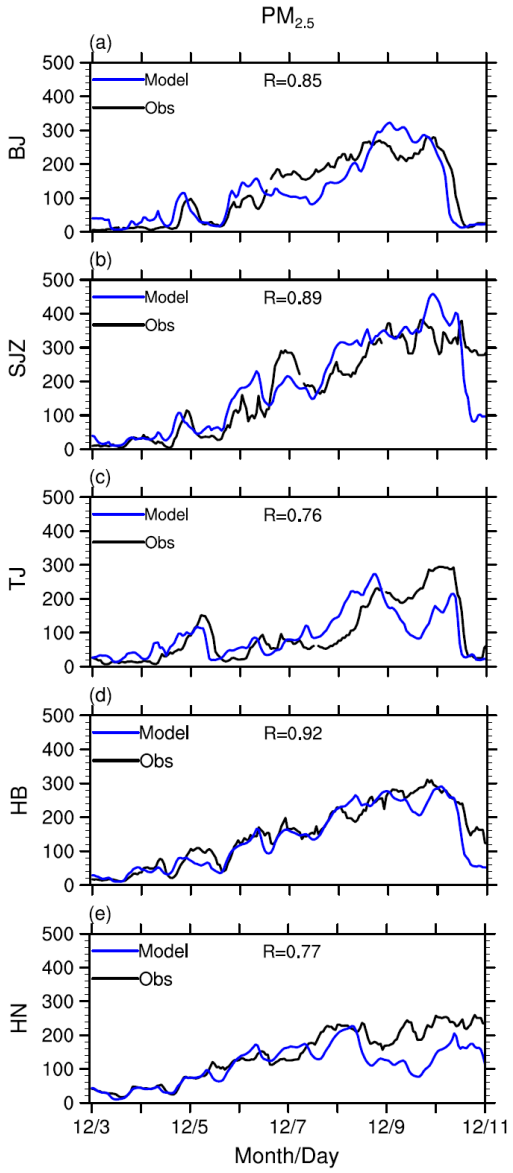

Fig. S5. Observed (black) and WRF-Chem simulated (blue) temporal variation of $PM_{2.5}$ (μg m^{-3}) at three major cities (a) Beijing (BJ), (b) Shijiazhuang (SJZ) (c)Tianjin (TJ) and two provinces (d) Hebei (HB) and (e) Henan (HN).

Line 279: Change “were overlay” to “were overlaid”.

Response:

Thanks, corrected.

Figure 5: Why does the AOD peak before the reduction in SW especially on 6th June? At Taiyuan, there is not much difference between Aero and NoAero simulations which may be because AOD at this site is likely not captured well by the model.

Response:

Thanks for your comment. The pollutant started to accumulate since 6th Dec., accompanied by the increment of AOD. However, the impacts of aerosol-radiation interactions on meteorological fields mainly occurred during daytime through its direct influence on radiation, especially shortwave (SW) radiation. Therefore, the peak timing of reduction in SW may not coincide exactly with that of AOD. In addition, the relation between AOD-induced radiation changes (through aerosol-radiation interaction) and AOD value is not linear.

Line 351: change "biases" to "biased".

Response:

Thanks, corrected.

Line 355: change "leaded" to "led"

Response:

Thanks, corrected.

Line 391: change "shown" to "showed".

Response:

Thanks, corrected.

Section 3.2.2 and related figures: Are the changes in different meteorological parameters statistically significant?

Response:

Thanks for your comment. To addressed this issue, we conducted three sets of 24-hour forecasts for a longer period lasting 27 days (Jan. 13th – Feb. 8th, 2017), with no AOD field (NoAero), climatological AOD fields (ClimAero) and WRF-Chem simulated hourly AOD fields (ChemAero) included, respectively.

The results indicated that the temperature was underestimated (overestimated) during daytime (nighttime) in NoAero experiment. The temperature is reduced by the aerosol-radiation interactions by inclusion of either climatological or WRF-Chem simulated AOD fields (Fig. S6a), which tends to increase the bias during daytime, and

decrease the bias during nighttime. However, the RMSE of temperature in ChemAero is lower than NoAero during the whole 24-hr forecast, particularly at 2000LT of nightfall with the reduction of RMSE reaching ~ 9%. While the RMSE in ClimAero is higher than that in NoAero during daytime (Fig. S6b-c). It is observed in Fig.S7a that, when averaging over Jan. 13th – Feb. 8th, the bias of 2-m temperature in ChemAero (0.48 ℃) is lower than those in NoAero (0.79 ℃) and ClimAero (0.52 ℃). Comparing the absolute bias difference (℃) between ClimAero and NoAero (ClimAero-NoAero), and between ChemAero and NoAero (ChemAero and NoAero) in Fig. S7b, the ChemAero shows more improvement than ClimAero in the simulation of 2m temperature, particularly during the events of Jan. 15-19, and Feb. 3-9. In regards of wind speed at 10m, the overestimated wind speed in NoAero was decreased in ClimAero and ChemAero, with the averaged bias of 1.49 m s $^{-1}$, 1.45 m s $^{-1}$ and 1.44 m s $^{-1}$, respectively (Fig.S7c-d). Moreover, the RMSE in ChemAero was lower than that in ClimAero, particularly during 1700 LT to 0500 LT (Fig.S6e-f). The detailed day-to-day comparisons confirmed the significant temperature improvement by inclusion of WRF-Chem simulated hourly AOD fields during several events, including Jan. 16-19, Jan. 25, Jan. 28, Feb. 3-4, and Feb. 7-9.

Overall, the one-month results are statistically significant which indicated that the simulation with the inclusion of WRF-Chem simulated hourly AOD fields outperformed other two simulations and showed more improvement on the forecast of surface temperature and near surface wind speed than the simulation with climatological AOD fields. We will work on this issue and perform more detailed evaluations and analysis in the future, aiming to facilitate the future inclusion of aerosol-radiation interactions in our regional operational Numerical Weather Prediction system.

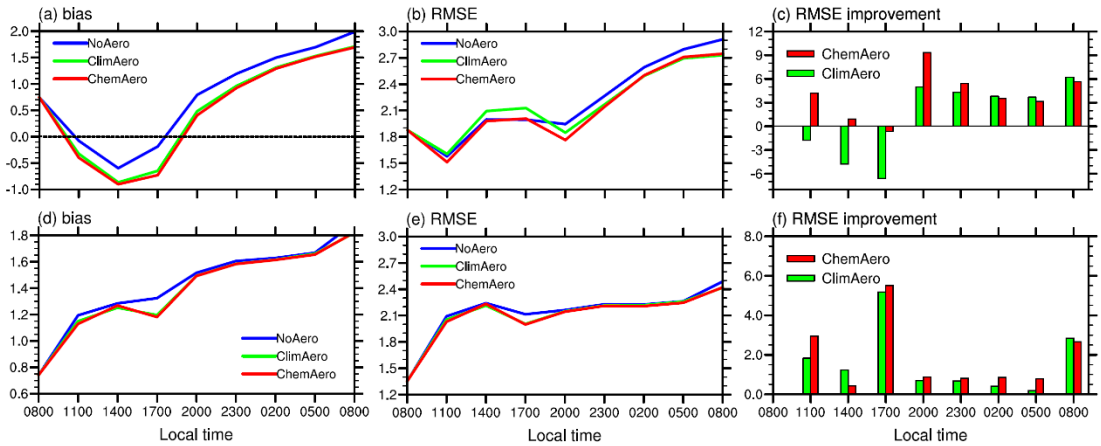

Fig. S6. Area-averaged (a) bias and (b) RMSE of simulated 2-m temperature (℃) in NoAero (blue), ClimAero (green) and ChemAero (red) over NCP area (defined in Fig. 1a), averaged

from Jan. 13th – Feb. 8th 2017, and the mean improvement (%) of (c) RMSE in ClimAero (green) and ChemAero (red) relative to NoAero. (d-f) are same with (a-c), but for wind speed at 10m (m s $^{-1}$).

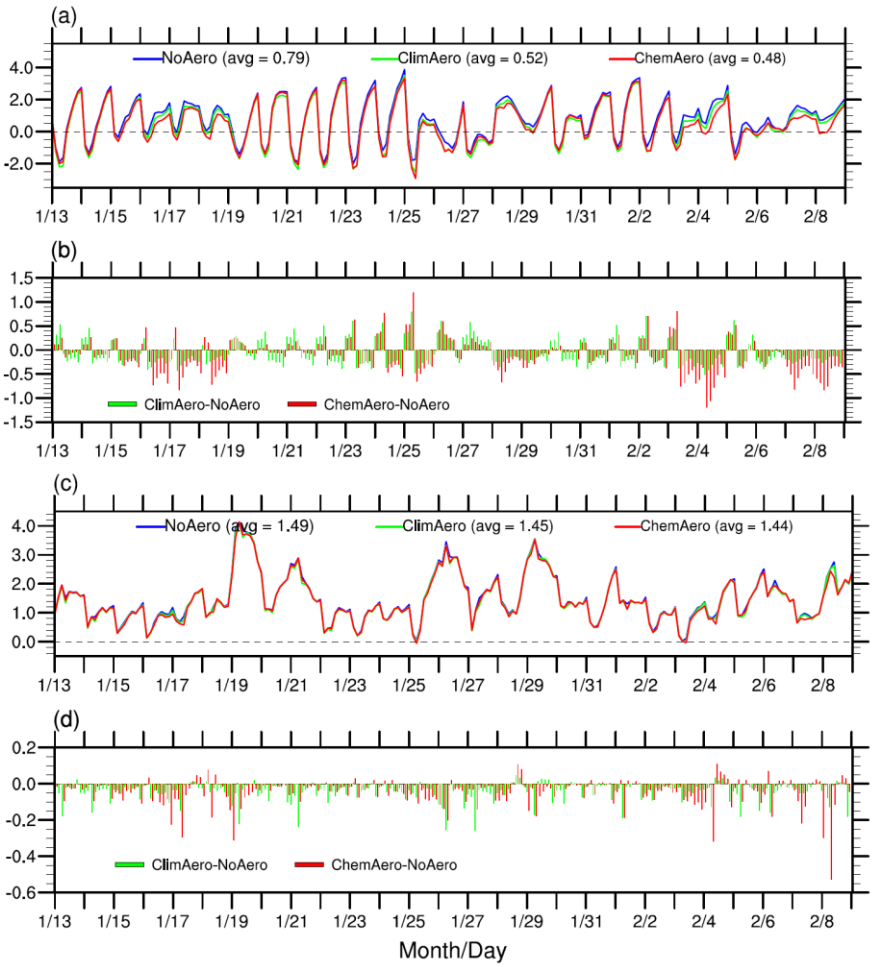

Fig. S7. (a) Temporal variations (00 UTC of Jan. 13th – 24 UTC of Feb. 8th, 2017) of area-averaged 2-m temperature bias (℃) simulated in NoAero (blue soild), ClimAero (green solid) and ChemAero (red soild) over NCP area (defined in Fig. 1a); (b) same with (a), but for the difference of absolute bias (℃) between ClimAero and NoAero (ClimAero-NoAero, green bars), and between ChemAero and NoAero (ChemAero-NoAero, red bars). (c-d) are same with (a-b), but for wind speed at 10m (m s $^{-1}$).