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)
Reviewer 2

Interactive comment on "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" by Yang Yang et al.

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General summary

The article is interesting and treats a topic of utmost relevance, that of aerosol impacts on Numerical Weather Prediction (NWP). The authors have analyzed in great detail a pollution case in Northern China during December 2-11, 2015 and examined the impact of including aerosol radiative forcing on several key meteorological variables. They found that aerosols have a large impact on shortwave radiative fluxes at the surface and consequently on 2m temperatures and wind speed using independent observations from various networks to establish that. These results are consistent with finding from other authors who highlighted the importance of a correct inclusion of aerosol fields particularly under extreme aerosol loads.

The paper deserves attention and with some refinements will be acceptable for publication. However, it is worthwhile to stress that case studies such as this may not be statistically significant, especially because extreme aerosol conditions were chosen. It would be necessary to run more cases, possibly entire seasons. I would encourage he authors to get in touch with the rest of the community and join an effort sponsored y WMO via various committees (WGNE, GAW and S2S) to run coordinate experimentation in regional and global models with the goal to gain a fuller picture of the aerosol pacts in NWP. Feel free to contact me directly about this.

Response:

Dear Angela,

We are really glad to be reviewed by you and get to know that different groups are working on this important topic. We will try to get in touch with you and the community in the near future and promote the operational application in our system; in this way, the long-term assessment of aerosol impacts over the northern China region would be possibly conducted routinely, not only confined on the scientific level.

We really appreciate your interest and insightful comments. To address this 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 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. S1a), 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. S1b-c). It is observed in Fig.S2a 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. S2b, 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.S2c-d). Moreover, the RMSE in ChemAero was lower than that in ClimAero, particularly during 1700 LT to 0500 LT (Fig.S1e-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.

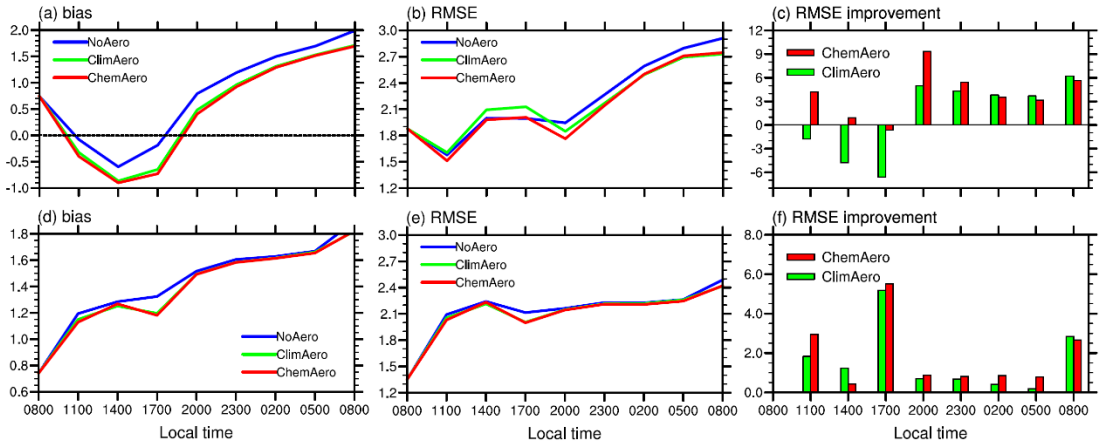

Fig. S1. Area-averaged (a) bias and (b) RMSE of simulated 2-m temperature (℃) in NoAero (blue), ClimAero (green) and ChemAero (red) over NCP area (defined in Fig. 1a), averaged from Jan. 13th – Feb. 8th 2017, and the mean improvement (%) of (c) RMSE in ClimAero (green) and ChemAero (red) relative to NoAero. (d-f) are same with (a-c), but for wind speed at 10m (m s $^{-1}$).

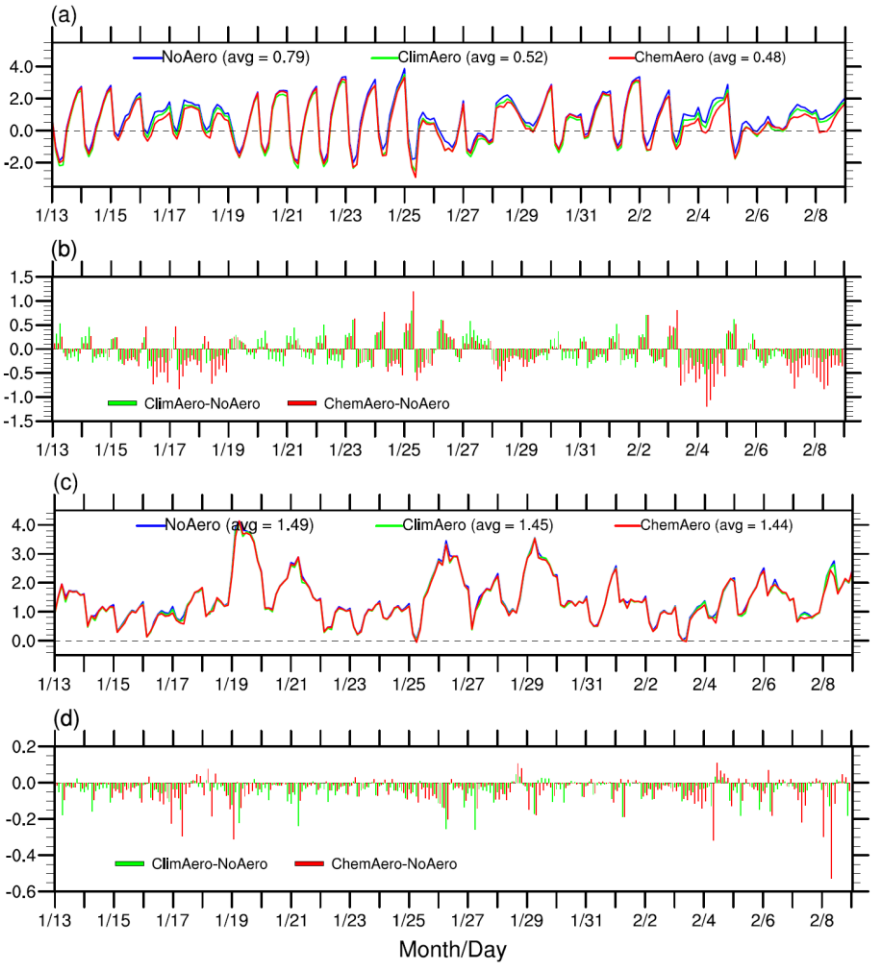

Fig. S2. (a) Temporal variations (00 UTC of Jan. 13th – 24 UTC of Feb. 8th, 2017) of area-averaged 2-m temperature bias (℃) simulated in NoAero (blue soild), ClimAero (green solid) and ChemAero (red soild) over NCP area (defined in Fig. 1a); (b) same with (a), but for the difference of absolute bias (℃) 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 $^{-1}$).

Minor comments and typos

line 22, high-frequency

Response:

Thanks, corrected.

line 66, episodic aerosol events

Response:

Thanks, corrected.

line 105, to facilitate the inclusion of…

Response:

Thanks, corrected.

line 116, was included

Response:

Thanks, corrected.

line 119 For these research studies using operational NWP systems, offline approaches were mostly used. Actually, in Remy et al 2015 and Mulcahy et al 2014 that was not the case and the interactive aerosols were run online.

Response:

Thanks for your comment. We have changed the sentence to "For these research serving for operational NWP systems, both online and offline approaches (that aerosol information were simulated by separate chemistry system and then offline coupled to NWP model) were widely used." In the revised manuscript.

line 143, in an NWP system

Response:

Thanks, corrected.

line 152, future applications

Response:

Thanks, corrected.

line 153, The remainder of the paper is organised: : : Please change all tenses in this paragraph to present.

Response:

Thanks, corrected.

line 168, National

Response:

Thanks, corrected.

line 169, Environmental - please re-run the paper through a spell and grammar checker to ensure that typos are corrected

Response:

Thanks, corrected.

line 171, with a higher

Response:

Thanks, corrected.

line 174 the Rapid Radiative

Response:

Thanks, corrected.

line 181 The RRTMG

Response:

Thanks, corrected.

line 185 was input

Response:

Thanks, corrected.

line 186 integral

Response:

Thanks, corrected.

lie 189 which was - please check that verbs are correctly conjugated

Response:

Thanks, corrected.

line 190 the same configuration

Response:

Thanks, corrected.

line 206 did you investigate the sensitivity of the model AOD to the choice of these ICs and BCs?

Response:

Thanks for the kind reminder! Actually for these heavily polluted region in winter, the initial and boundary conditions are really not so important as in the clean regions, since the pollutant accumulation are usually associated with the high-intensity emission emitted and unfavorable meteorology conditions. For boundary condition, the default profile in WRF-Chem model seemed Okay for this region. For initial conditions, several-days spin-up staring from clean case and going-on for 3-4 days accumulation is usually close enough to real case. We have tried MOZART boundary condition for summer and did see some differences. We may test the sensitivity of the modeled AOD to the choice of chemical ICs and BCs in the future.

line 216 were CARSNET (https://www.atmos-chem-phys.net/15/7619/2015/) observations available over the area? if yes, why were they not used?

Response:

Thanks for your comment. Currently, we don't think the CARSNET dataset is publicly released and we don't have official access to it neither, but we agree with you that the collaboration is helpful in research work. To address the importance of simulated AOD accuracy, we added the evaluations of modeled AOD and aerosol extinction coefficient against MODIS and CALIPSO satellite-based products, respectively.

The modeled AOD was evaluated against MODIS Terra and Aqua (Fig. S3). 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. 6^{th}, then the center moved to Hebei and Beijing on 7^{th} 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. S3r-s).

Fig. S4 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. S3-4 and the discussion in the revised manuscript (around L247- L255 and around L255-L264).

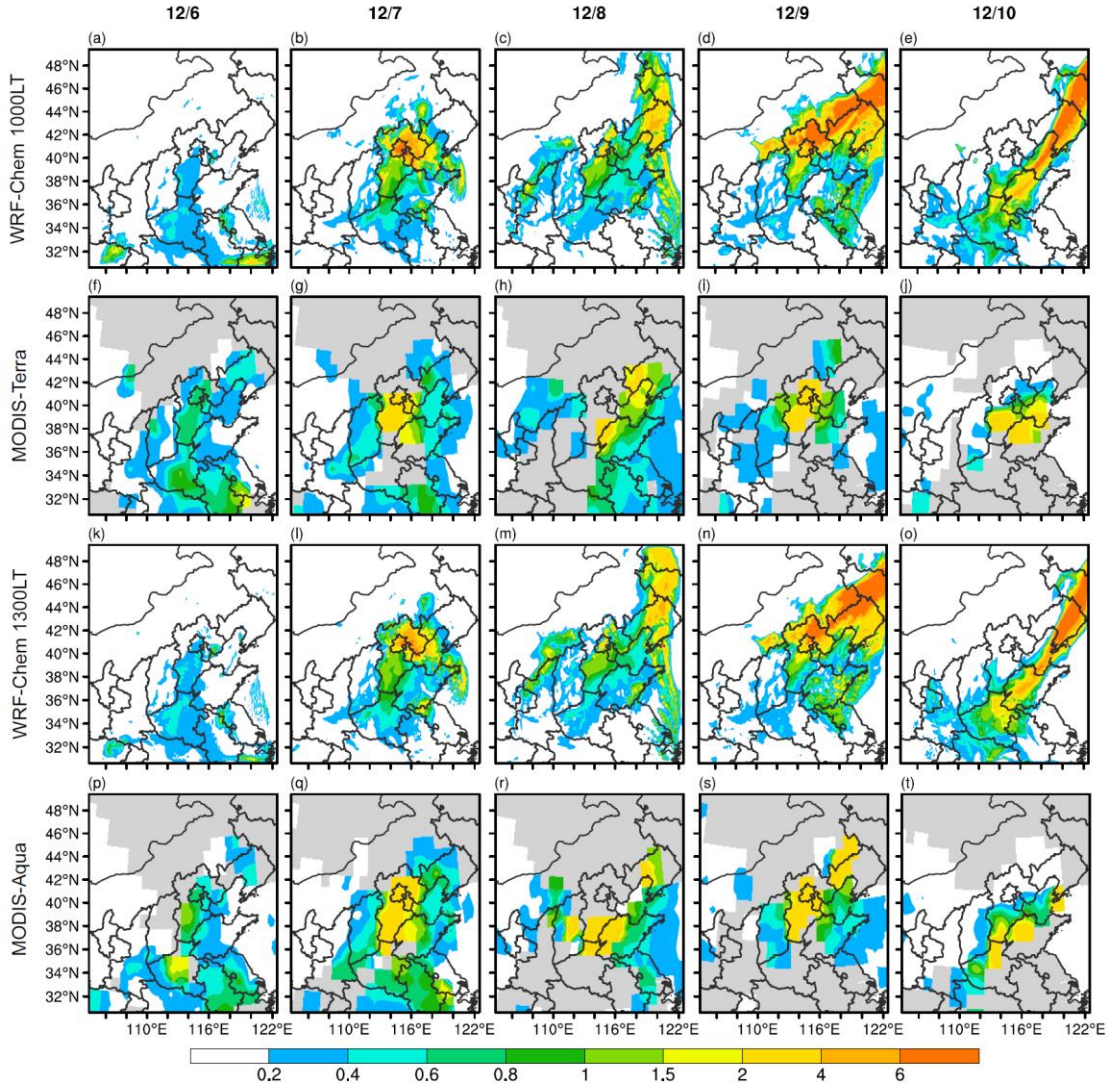

Fig. S3 The WRF-Chem simulated and MODIS observed spatial distribution of AOD on 6th-10th December (from left to right). The first (a-e) and third rows (k-o) are WRF-Chem simulations at 1000LT and 1300LT (MODIS path times) respectively. The second (f-j) and fourth (p-t) rows are MODIS Terra and Aqua observations, respectively. Gray areas in (f-j) and (p-t) denote the missing values.

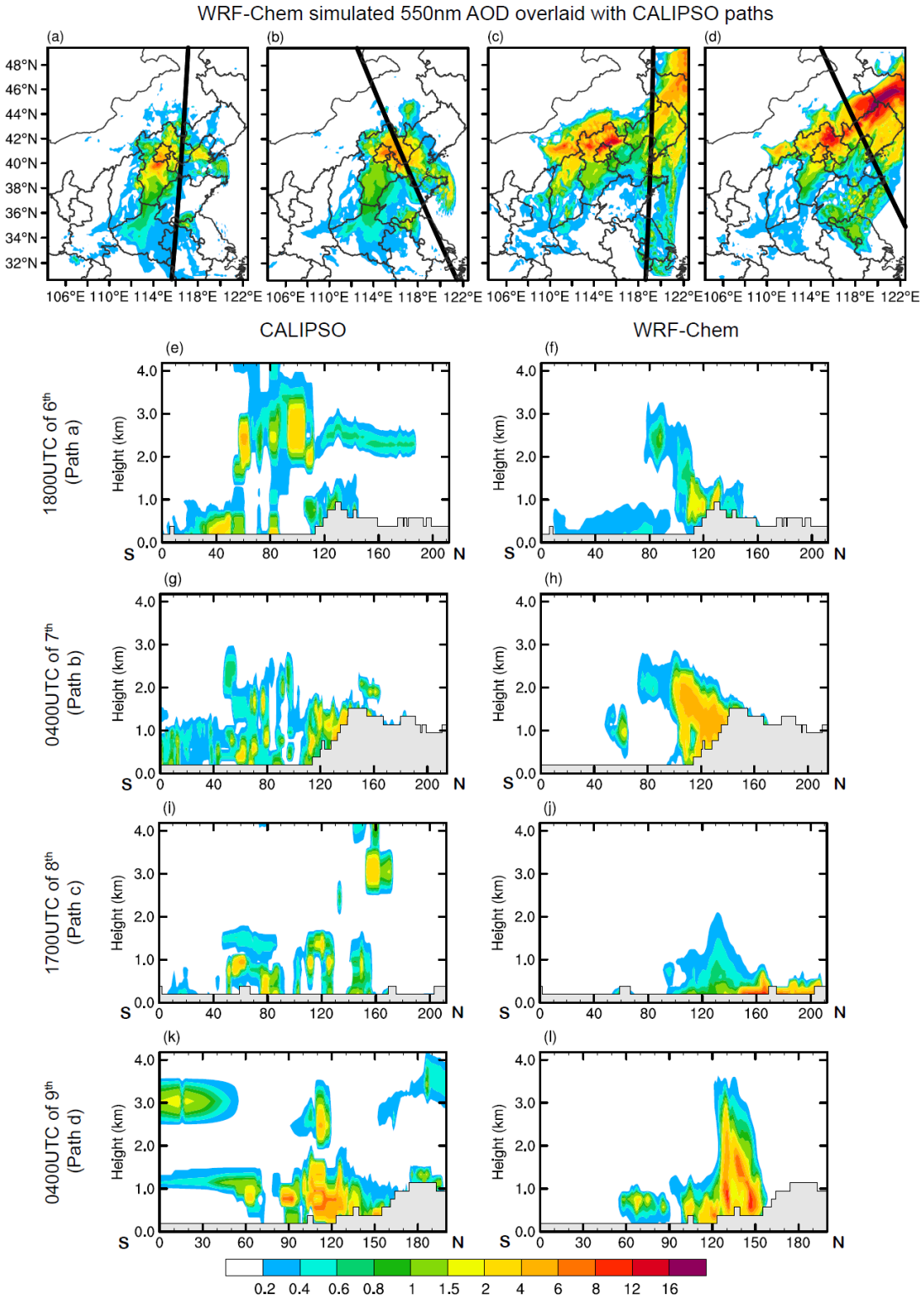

Fig. S4 The WRF-Chem simulated 550nm AOD (shadings) on (a)1800UTC of 6th, (b) 0400UTC of 7th, (c)1700UTC of 8th, (d) 0400UTC of 9th December overlaid with CALIPSO paths (black thick solid). (e-l) denote the corresponding vertical distributions of aerosol extinction coefficient at 550nm from (e, g, i, k) CALIPSO and (f, h, j, l) model simulations. Gray areas in (e-l) denote the terrain.

line 237 / Figure 2 I think it would be good to have extra data from CARSNET if possible

Response:

Thanks for your insightful comment. We added the evaluations of modeled AOD and aerosol extinction coefficient against MODIS and CALIPSO satellite-based products, respectively. Please see more detailed discussion above.

line 244 most of them, do you mean the observations during the peak? See comment above.

Response:

Yes, the observation of AERONET are quite limit during the peak. We added the evaluations of AOD simulation with MODIS and CALIPSO satellite-based products. Please see more detailed discussion above.

line 245 were similar to

Response:

Thanks, corrected.

line 247 you need more observations to establish that

Response:

Thanks, we agree with you that the statement seems arbitrary without more observations here, we have deleted this sentence in the revised manuscript.

line 265 do you think this was because of the emission inventories used or the skill of the model or both? Please comment.

Response:

Thanks for your comment. From our experience, these biases in two directions are related with both the emission inventories used and the skill of the model, but more diagnostic should be conducted to gain solid conclusions. We have added the comment "It was note that there exits slight overestimation (underestimation) of the peak magnitude during 9^{th} to 10^{th} 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." in the revised manuscript.

line 286 In the NoAero experiments were the aerosols completely missing from the simulation or was a climatology used?

Response:

NoAero experiments were the aerosols completely missing from the simulation, we have added the clarification about this issue as "The only difference between the two sets of forecasts is whether the aerosol radiative feedback is activated (Aero, with WRF-Chem simulated hourly AOD fields as input fields) or not (NoAero, no aerosol included), and other schemes remained the same." in the revised manuscript (around L214-L217).

line 302 if a climatology were used would this discrepancy be less severe? I am assuming that in the NoAero simulations there were really no aerosols.

Response:

Thanks for your comment. NoAero experiments were the aerosols completely missing from the simulation, we agree with you that the discrepancy of shortwave radiation would be less severe if a climatological AOD were used.

line 304 this type of bias in SW fluxes is huge

Response:

Thanks for your comment. The polluted episode is a severe event with the maximum of AOD exceeding 8 at Beijing. Therefore, the SW fluxes were profoundly overestimated due to the missing processes of strong forcing from aerosol-radiation interaction, in the NoAero experiment. Actually we suspect the aerosol-cloud interactions may play some role in reality as well.

line 321/Figure 6 At some stations the bias in SW fluxes is not improved as much as in Beijing - do you have an explanation for that?

Response:

Thanks for your comment. The magnitude of changes in SW radiation induced by aerosol-radiation interaction is associated with the magnitude of AOD. The AOD at Beijing is much higher than those of Tianjin, Taiyuan and Jinan. Therefore, the biases

in SW fluxes at these stations were not improved as much as that at Beijing. We have added the discussion about this issue in the revised manuscript (L351-L352).

line 341 are discussed

Response:

Thanks, corrected.

line 368 is this an average value? With the biases in SW radiation being so large I would have expected higher temperature biases.

Response:

Thanks for your comment. The temperature bias is the averaged bias over NCP domain and for the whole period during 6^{th} to 10^{th} December. We have clarified this issue in the revised manuscript.

line 420 / Figure 15, the wind profile at Beijing is quite different from observations in both Aero and NoAero experiments, do you have an explanation for that?

Response:

Thanks for your comment. The wind speed at lower layers is generally overestimated in our operational NWP system, but with much lower magnitude than those shown in Fig. 15. The large bias in Fig. 15 is probably related with the problem about the presentation of boundary layer processes for this period in the model.

line 450 very nice discussion of the impacts on the vertical stratification

Response:

Thanks for your comment.

line 461, please specify if an aerosol climatology was used in NoAero

Response:

Thanks, NoAero experiments were the aerosols completely missing from the simulation, we have clarified this issue in the revised manuscript (L495-L499).

line 520 the fact that aerosol-cloud interactions were not included in the study should be mentioned also at the beginning.

Response:

Thanks, we have added the statement “It is noted that the aerosol-cloud interactions were not included in the study” in the revised manuscript (L217-L218).