Response to Referee #1

We thank Referee#1 for some very insightful and constructive comments on our discussion paper (Lee et al., 2014). All the points are well taken, and we have made a number of revisions to the paper to clarify the points raised in the review. We reproduce the referee's questions in italics followed by our responses. All authors listed on the manuscript have discussed and concurred with the revisions and response being submitted.

"This study examines the effect of biomass burning in Southeast (SE) Asia on regional climate during the pre-monsoon period using a climate model with very coarse resolution. It shows significant impact of aerosol radiative effects on precipitation spatial distribution and circulation pattern, similar to many other studies. Aerosol indirect effect is only briefly demonstrated with radiative forcing. To me, the paper is not completed yet. How aerosol indirect effect changes circulation, water vapor, and precipitation patterns is of more interest and larger uncertainty, which should be in-depth examined and compared with aerosol radiative effect. "

- The resolution of GCMs is by default course compared to regional models. However, compared to a high resolution regional model, a GCM provides two advantages i) it captures better the evolution of inter-seasonal phenomena such as monsoons ii) it allows global interactions and feedbacks. Indeed, studies such as ours almost always lead to further questions and in that light this and many other comments made by Referee are useful in guiding further analysis and elaboration. Examining the influence of aerosols on the simulated Southeast Asian rainfall and circulation was our primary goal.

We believe some questions have arisen because we decided the design of 'High' and 'Zero' experiments. It has the drawback of making more difficult direct comparisons to observations very much the way the reviewer suggests. However, the BBA signal in year-to-year variations was not significant compared to the interannual variability of the simulated atmosphere. We therefore decided to examine the BBA anomaly arising from the no BB versus high BB emission scenarios. This enhanced the impact of BBA, so that we could positively isolate the statistically significant changes in the SEA region. We now make the relevant discussion more comprehensive following the Reviewer's guidance.

"In addition, there are many arbitrary assumptions for explaining the model results. Many of them can be validated by a little in-depth data analysis. See examples provided in the detailed comments below. This study seems to lack goals. It does not appear to link the modeling study with any observational phenomena/hypothesis. It also does not have some necessary introduction for the recent understanding/progress of this area.""

- It was difficult to see the effect of BBA on clouds and precipitation on monthly and seasonal time-scales even in the observational data because the real data are affected by large interannual variations induced by s sea-surface temperature variability. In this study, due to practical restrictions, we tried to separate aerosol effect by running the model with climatological sea surface temperatures. We also revised the introduction to include other recent studies per the reviewer's recommendation.

“Much of information about model and experiment design is missing or not clearly described. For example, is GOES-AGCM is a regional model of GOES or still a global climate model?”

- The GEOS-5 AGCM is a global climate model that can be constrained with any data such as SSTs or aerosols. The model and its parameterizations are discussed in Sud et al. (2013) which discussed the GEOS-5 AGCM physics modules. It is always challenging to provide brief descriptions of the model’s capabilities in a study focused on simulating climatic effects of aerosols, but in our revision we made an effort to add more details as suggested by the reviewer.

“What is used for cumulus parameterization? Does the cumulus parameterization consider any aerosol impacts?”

The cumulus parameterization of our model is the “Microphysics of clouds with Relaxed Arakawa–Schubert moist convection; it is upgraded with prognostic Aerosol Cloud interactions (McRAS-AC, Sud et al., 2013).” (P32888). It has well-verified capabilities to simulate the key aspects of direct indirect effects of aerosols on clouds. Aerosols affect cloud particle size and number density that in turn affect autoconversion, the initiator of precipitation that subsequently affects the rest of the cloud microphysics. All this is comprehensively discussed and validated in Sud et al. (2013). The cloud microphysics parameterization equations are the same for convective and stratiform processes. In convective towers vertical velocity and entrainment are computed level-by-level, however, prognostic CCN/IN are produced in response to condensation/deposition and available aerosols; the calculations are explicit and all levels are vertically interactive. As described in the last paragraph of the ‘Summary and discussion’ (P32904) our GCM employs some simplifying assumptions that we intend to improve as a result of ongoing model development. For example, convective mass flux in the current ‘Relaxed Arakawa-Schubert’ scheme has quadratic growth of entrainment using an entrainment parameter whose value is adjusted to make cloud buoyancy vanish at the detrainment level being tested. However, the buoyancy generated in the convective ascent, called cloud work function, must exceed an observations-based critical cloud work function for the cloud to form. A convective cloud is disallowed if it fails the above test. Whereas aerosols can increase cloud particle number density, suppress autoconversion and thereby increase liquid cloud water loading, the latent heat of freezing released does not affect ascent velocity, cloud height and entrainment. This shortcoming is being currently addressed in our model development research.

“Also, I would like to understand if there are any new model developments for this study. Please describe as a separate paragraph and label clearly if there is.”

- Sud et al (2013) showed key aspects of model developments for aerosol-cloud interactions and cloud physics in McRAS. The paper also showed sensitivity studies with interactive aerosol module and modified aerosol size distribution for better representation of CRE. The model used in this study includes all these upgrades.

“Therefore, the paper needs to go through very significant revisions to reach a form that can be published. Hope these comments are helpful to shape the study.”

- Our simulations were designed to assess the sensitivity of SEA pre-monsoon (MAM season) rainfall to BB emissions. Nevertheless we have followed the reviewer's recommendations and revised the paper substantially, particularly in areas where both reviewers made similar comments.

"Too many acronyms in this paper and it is very hard to follow. In addition, it would be much easier for readers if the authors follow terminology symbols that are generally used in literature. For example, liquid cloud effective radius can be represented as rel instead of LCER. Use cloud, ice and total number concentrations are generally represented with Nc, Ni and Ntot (not the long acronyms used in this study)"

- Acronyms have been replaced by common symbols such as N_c and R_{eff}, as suggested.

"Section 1, Introduction does not include information about what are aerosol radiative and indirect effects. There is also no brief introduction of the current understanding of aerosol impacts on deep convective clouds and straticumuli/stratiform clouds since these clouds are the study objects. There are significant progresses that have been made recent years based on process-level modeling studies and observational studies in this field. Please conduct literature search."

- We have addressed this deficiency by including an additional paragraph with references to other related works.

"Section 3.1: The purpose of the section should be validation of model simulations. I do not see this goal from the text and figure 2. Does climatology data include high BB cases? I suppose it should be. Then what is the meaning of comparing with climatology? Why not compare with the observations of the corresponding model time period?"

- Our goal is to investigate BBA effect in the region at monthly to seasonal time scales. The largest factor at these time scales would be tropical SST for both observations and model simulations. To be consistent with employing climatological SST to remove the SST forcing in the model, in observations higher BB emission days are selected from every year and compared with climatology, thus also removing SST forcing which isolates BBA effects from the interannual variability.

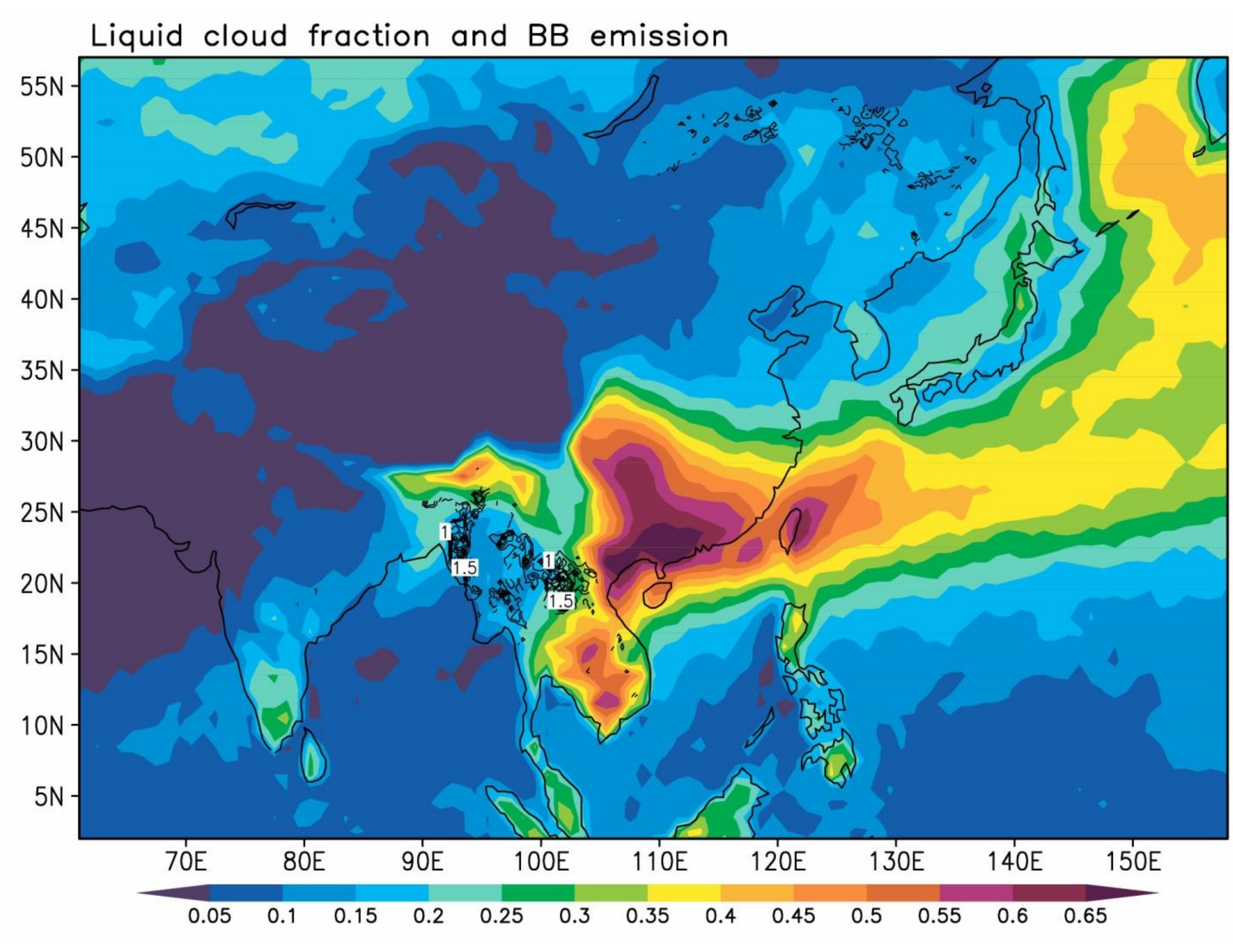
"Figure 3: why is droplet effective radius increased a little over the ocean near coast? It is unusual. Clouds should be shallow generally and the place is the downwind of the BB sources. Droplet size should be significant decreased. There are some observational studies that have shown it."

- We realize that cloud droplet size is expected to decrease when aerosol loading increases. In Fig. 3a, the area with light red is where BBA are transported. We can see decreased droplet size over the area in Fig. 3b. The area the referee is pointing to, where the droplet effective radius increases slightly over the ocean near coast is outside the BBA area. Our model has its own internal variability in regions where the BBA forcing is absent. Presumably, wherever the statistical significant level is low, the anomaly represents noise.

“P32895, Line 6-9, what is your justification for preexisting clouds? What Figure 4 shows is that cloud water peaks around 800 mb, where strongest condensation probably occurs. It does not say anything if clouds occur first or BB aerosols first.”

- While we appreciate the question, we do not understand the need to discuss production of preexisting cloud. The cloud cover is generally composed of stratiform, low-altitude clouds associated with frontal systems that originate in China (Hsu et al. 2003) while BBA is transported from the source region. Please refer to Fig. R1.1 below. Colors indicates seasonal (March and April) liquid cloud fraction from 10 years of Terra/MODIS. Black contours represent BB emission which is same as in Fig. 1a. The area of high cloud fraction is separated from the BB source area due to topography (Fig. R2.3a). Whereas new cloud formation co-occurs with BB activity somewhat intermittently, the cloud cover stays more or less steady. (Fig. R2.3b). It is for this reason we argue that “BBA are lifted aloft by topography oriented in a north to south direction, and act as an additional source of CCN in pre-existing clouds“.

Fig. R1.1 Liquid cloud fraction (shaded) from Terra/MODIS and BB emission (contour) on March and April



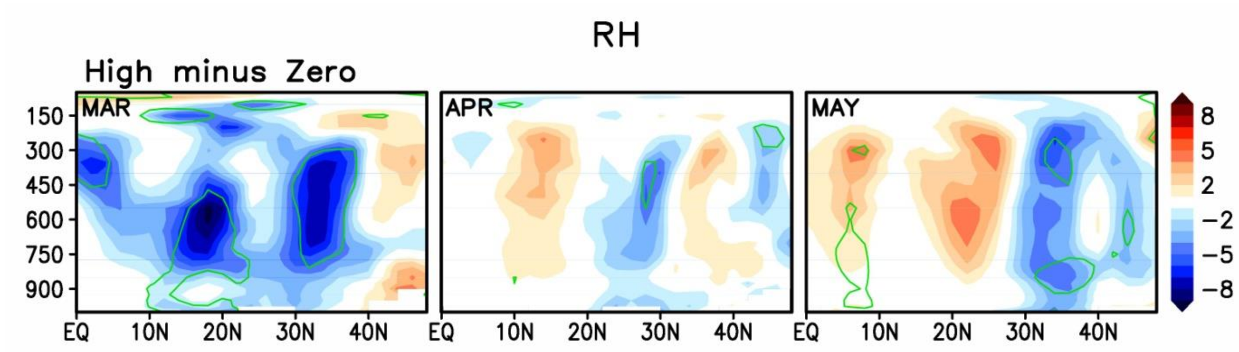
“P32896, Line 11, change “May aerosol concentrations” to “Aerosol concentrations in May”. There are a few these kinds of statements that should not appear in a scientific paper. “

- Revised as suggested.

"P32896, Line 15-20, since you attribute the negative CDNC and LWP to reduced cloud fraction and RH. Please present these figures. In addition, what is the reason for the larger stability of the lower atmosphere? Semi-direct effects? If so, there are many such studies, which could be cited."

- The cloud fraction change is plotted in Fig. 5e, while the reduced moisture is shown in Fig. 9 represented by blue shading. The suggested RH change figure (which due to space limitations cannot be included in the proper paper) is presented in Fig. R1.2. A dry anomaly caused by BBA can be seen during the period of study, especially in March. Our explanation as to why and how total cloud fraction decreases is provided in Section 3.4. In short, it is an outcome of both the layer temperature and moisture changes having opposite effects on RH, which makes it hard to isolate the semi-direct effects.

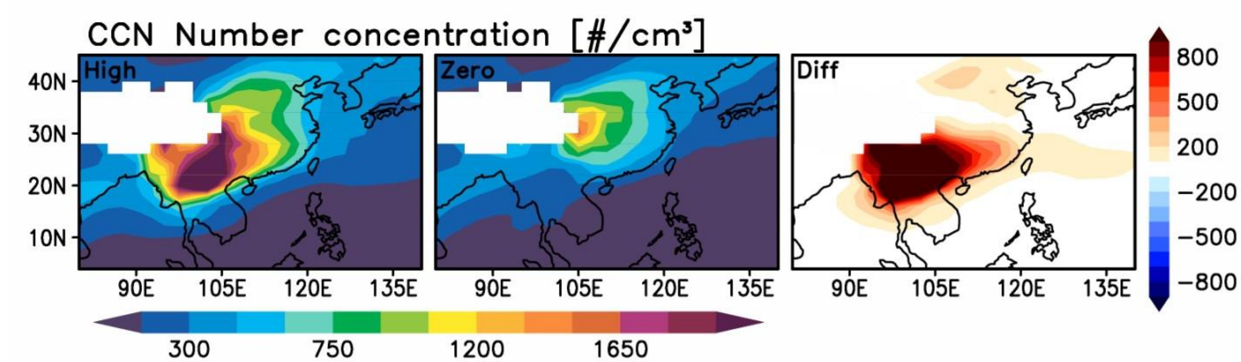
Fig. R1.2 Zonally-averaged profiles of RH (shading) from HighBoth minus ZeroBoth experiments over the longitude sector 100–120E for March, April and sector 110–140E for May. Green contour mark regions of > 95 % significant in a student's t test.



"P32896, Line 21, now you use Nc and Lc (you used CDNC and LWC before). Please clarify and use the consistent symbols. In addition, you did not show the increase of CCN also. So, please add CCN to Figure 4. I'd like to see if and how much CCN is increased with high BB emissions. This is important to examine the contribution from aerosol radiative effect and indirect effect."

- Symbols and acronyms are revised as suggested. CCN was the one of the candidate variables to include in Fig. 4. But because the difference maps are very similar with AOD (Fig. 4a), we decided to plot actual cloud drop number concentrations used to calculate autoconversion rate. The process of calculating how many particles are activated to become cloud droplets is truly an involved calculation, but its theory is well accepted and validated. It is based on Fountoukis and Nenes (2005) following Nenes and Seinfeld (2003). Please refer Fig. R1.3 showing potential CCNs. As expected, high CCN number concentration can be seen in 'High' experiment particularly over the source region. The white area lacks data due to high topography.

Fig. R1.3 CCN number concentrations of HighBoth, Zeroboth and the difference between two on FMA.

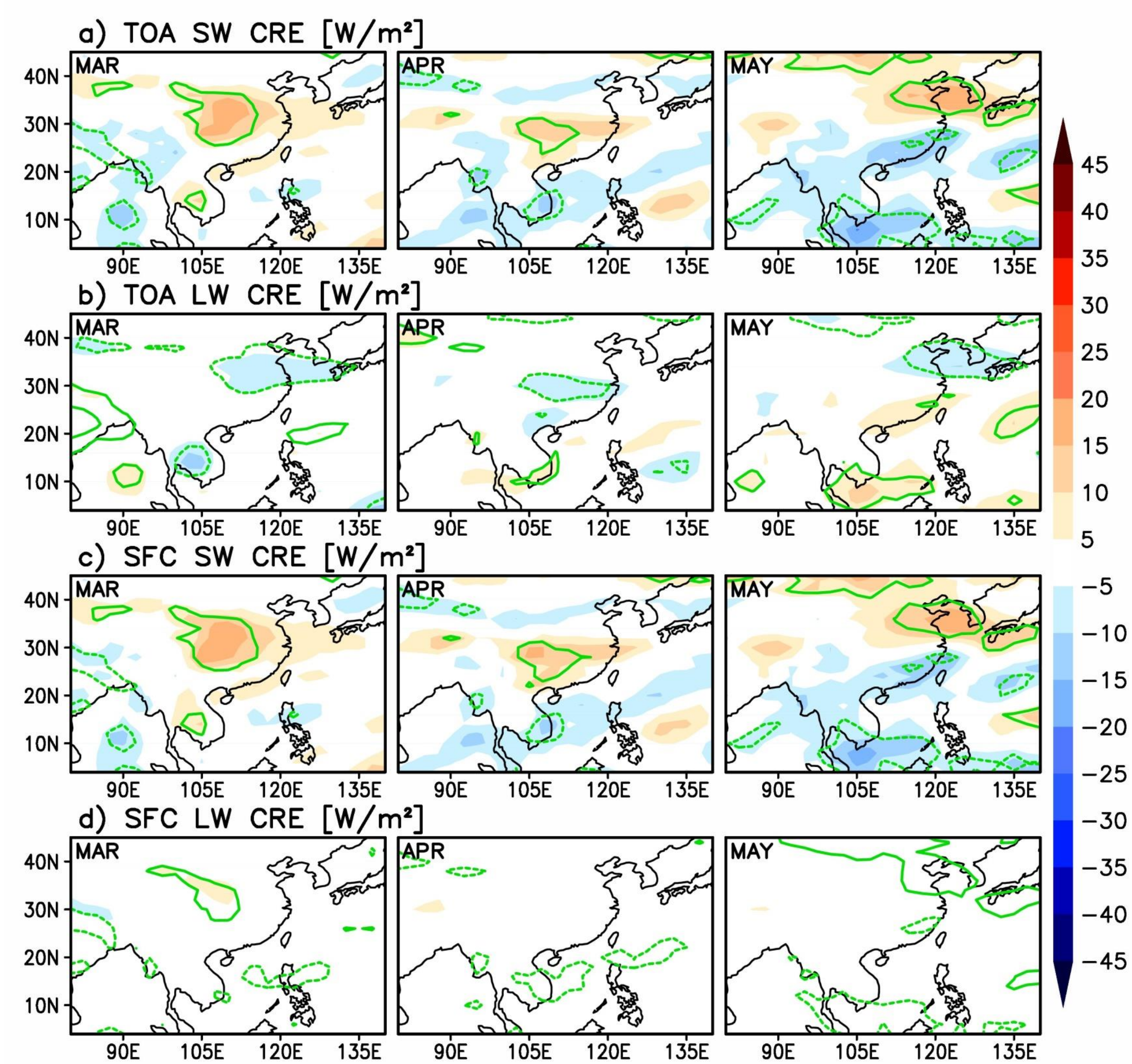


"Figure 5, I do not understand the figure caption. What is COSP? This figure should be from the model simulations. Since cloud fractions at higher level and lower level have very different radiative effect. Please break cloud fraction into the lower level and high-level cloud fraction to give in-depth insight about how they contribute to the radiative forcing at TOA, atmosphere and surface shown in Figure 5."

- COSP is an acronym for the "CFMIP Observation Simulator Package"; CFMIP in turn stands for "Cloud Feedback Model Intercomparison Project". Because of significant differences between the ways clouds are observed and represented in models, "satellite simulators" are used to transform the model fields in a way that makes them more comparable to observations. (Klein et al., 2013). The model fields compared with MODIS data are from MODIS simulator in GEOS-5 AGCM. We revised the manuscript to define COSP more comprehensively.

We initially had produced several panels of SW, LW radiative flux maps, but decided to plot only the net radiation and total cloud fraction to limit figures to a reasonable number. In the revised paper we added a table of radiative fluxes for additional insight. Overall changes in CREs are smaller than net radiative flux changes mostly coming from aerosol direct effect in Table 2. (also in Fig. R1.4) Please refer Fig. R1.4 which shows SW/LW breakdown. SW CRE changes can be explained by total cloud fraction differences (Fig. 6). LW CRE changes are even smaller than SW CRE changes. Figures of net radiation (Fig. 5) and cloud fraction (Fig. 6) and the tables for SW/LW and all sky/clear sky breakdown form the basis of Section 3.3 and 3.5.

Fig. R1.4 HighBoth minus ZeroBoth representing BBA effects on a) TOA SW CRE, b) TOA LW CRE, c) SFC SW CRE, and d) SFC LW CRE (units are Wm^{-2}). Green contour mark regions of >95% significant in a student's t-test.



"P32896, Line 26-28, since the precipitation anomaly pattern is different in each month, which month have you chosen to compare with the satellite observations? Therefore, you should provide figures for the observations accordingly in each month. Otherwise, you should not make such comparison."

- In section 3.1 we compared FMA mean precipitation change between observations and model because the FMA period is the active BB season and would therefore make for a valuable comparison. But we also show details of model simulation by month.

"P32898, Line 1, you can not arbitrarily say that the atmospheric heating is totally from aerosol absorption without looking into it. Increase clouds in the higher levels can cause atmospheric heating also. You need to break into clear-sky and cloudy-sky to get idea how much direct heating from aerosol light-absorption. "

- Please refer to Table 2 where radiative fluxes are decomposed. Absorbed SW into atmosphere in all sky condition is 15.1 W/m^2 while for clear sky is 17.1 W/m^2. In this case therefore the cloudy part doesn't heat as much as the clear part.

"Figure 8, I am surprised that BB in the south impact the surface temperature in the far north so much. How do you explain it?"

- Only the green contoured area shows statistical significant change by BBA. If an anomaly doesn't meet statistical significance criteria, we consider it as model internal variability which is unrelated to BBA forcing.

"P32899, please explain a strong LW warming at 700 mb (but not a SW warming)?"

- Orange line represents SW while red line LW. Strong SW warming is caused by aerosol direct effect.

"P32900, line 20, it is not clear where the downwind is since precipitation in many places are reduced. Suggest plotting wind field to show wind directions and circulation."

- Downwind direction in the description is northeast. We have now added wind fields in Fig. 5a.

"P32900, Line 24, there is no such process called "rain re-evaporation". Please change to "rain evaporation". Also, this assumption can be examined by plotting the changes of the below-cloud RH."

- Revised as suggested. Please refer to Fig. R1.1 for RH plot. Since the manuscript includes moisture change plot, RH was not plotted.

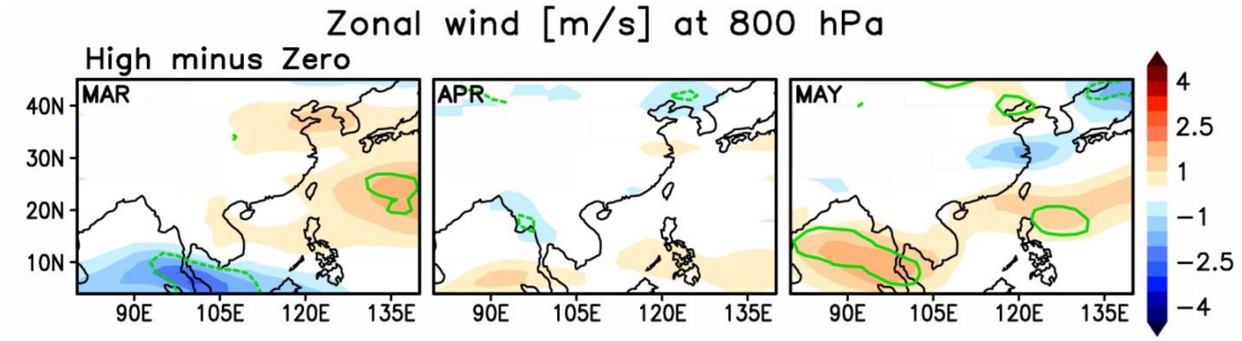
"P32901, last paragraph, smaller IE could also be due to the cloud fraction parameterization does not consider much aerosol impact. So, your results here does not mean that IE effect is smaller than direct effect in reality or detailed process models. This limitation needs to be discussed. Also, IE can be warming (higher –level clouds) or cooling (lower-level clouds). The cancellation can make the sum is small. This can be examined in my previous suggestion. If your cumulus parameterization does not include aerosol impacts, then it may explain why you only see reduced precipitation by IE because your IE effect here only limits to the large-scale stratiform clouds (many CRM studies have showed increased precipitation for deep cumulus clouds). This discussion should be added too. Therefore, I suggest a discussion section. Please also provide what cloud fraction assumption is used in Model Description. "

- We agree with the above analysis and discuss it as suggested. The current convective module needs upgrades to better reflect all aspects of aerosols. For example, it doesn't affect the cloud fields by aerosol-induced convective invigoration. We discuss this limitation in the last section. However as described in the model description, aerosol - cloud interactions are implemented into both stratiform and convective towers topped by detraining convective anvils. Since the area doesn't have much convective activity in the particular season our model simulations are not affected much by the influence of BBA on deep convection. The model description section is revised accordingly.

"Section 3.4, to more clearly examine the circulation change, besides Figure 10, spatial distribution of wind field should be shown."

- Zonal wind field is not shown because it doesn't exhibit statistically significant change. Please refer Fig. R1.5. We plot instead meridional and vertical circulation change and their significances in Fig. 9.

Fig. R1.5 Same layout as in Fig. R1.4 but for zonal wind at 800 hPa.



"Section 3.5, this section is way too simple and does not provide much information. Only the radiative forcing is provided for the two sensitivity runs for the indirect effects. It is worth analyzing how precipitation, water vapor, and circulation are changed by considering only aerosol indirect effects and what the differences are compared with the runs with the combined effects."

- We have done a few analyses of this kind, but include only the details where BBA effect is significant. The variables are described in Section 3.5 are precipitation, surface temperature, evaporation, moisture, heating rates and temperature in Table 4.

"BBA and BB effects are used for the same thing (sometimes it is said as BBA effect and sometimes said as BB effect. It is very confusing. Please clarify to be consistent."

- Revised as suggested.

References

Fountoukis, C., and Nenes, A.: Continued development of a cloud droplet formation parameterization for global climate models, Journal of Geophysical Research-Atmospheres, 110, doi:10.1029/2004JD005591|10.1029/2004JD005591, 2005

Hsu, N., Herman, J., and Tsay, S.: Radiative impacts from biomass burning in the presence of clouds during boreal spring in southeast Asia, Geophysical Research Letters, 30, doi:10.1029/2002GL016485, 2003.

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