Responses to the Comments of the Anonymous Referee #1

We very much appreciate the constructive comments and suggestions from this reviewer. Our point-by-point responses to the reviewer's comments are as follows (the reviewer's comments are marked in Italic font).

Comments:

This study investigates the impact of biomass burning aerosols on convective systems in the Sumatra and Borneo regions of Southeast Asia using the WRF-Chem model. Considering the large uncertainty in the interactions between aerosols, particularly those from biomass burning, and convective clouds, this study advances our understanding of the complicated and competing physical processes that governs the net effect of biomass-burning aerosols. The manuscript is generally well written. I think it can be considered for publication after the author addresses the following comments and suggestions.

1. Abstract: The descriptions after Line 45 are much too general. The author mentioned several times that fire aerosols have "significant/substantial impacts" on convection. What exactly are these impacts? I believe the author should summarize their main findings here so that the abstract can be more informative.

We thank the reviewer's suggestion. We have modified the abstract as: "Results from selected cases of convective events have shown significant impacts of fire aerosols specifically on the weak convections by increasing the quantities of hydrometeors and rainfall in both Sumatra and Borneo regions. Statistical analysis over the fire season also suggests that fire aerosols have impacts on the nocturnal convections associated with the local anticyclonic circulation in the western Borneo and then weakened the nocturnal rainfall intensity by about 9%. Such an effect is likely come from the near surface heating by absorbing aerosols emitted from fires that could weaken land breezes and thus the convergence of anticyclonic circulation."

2. Line 173-175: How did you treat emissions from the flaming vs smoldering phases when calculating plume rise? A previous study (Shi et al., 2019, JGR-Atmospheres, DOI 10.1029/2019JD030472) has shown that the fraction of smoldering-phase emissions has a large impact on plume rise and fire-induced aerosol concentrations.

The current plume rise algorithm in WRF-Chem is based on the burning vegetation types not burning phases. In the reality, most peatland fires burn in smoldering-phase and most fire aerosols concentrate near surface. Shi et al. (2019) pointed out that not considering the characteristics of smoldering phase of burning in the model could lead to underestimated fire emissions and thus near surface fire aerosol concentration.

Our study has considered the first issue (the vegetation types) and we have made corresponding modification to WRF-Chem plume model. As mentioned in the manuscript, for peatland fire, we have set its heat flux as 4.4 kW m^{-2}, which is the same as that of savanna burning while differs significantly from that of the tropical forest burning in 30 kW m^{-2}. Furthermore, we have limited the plume injection height of peat fire by a ceiling of 700 m above the ground based on remote sensing retrieval from Tosca et al. (2011). The injection height for tropical peat fire in our modeling was thus derived based on this new algorithm. We agree with the reviewer that the phase of burning should be considered more carefully in future efforts in deriving fire emission inventory. We have added a sentence in Lines 187-190 of the manuscript as: "Note that the current fire emission inventories could underestimate near surface fire aerosol concentration by ignoring some of the characteristics of smoldering burning as well (Shi et al., 2019)."

3. Line 185-186: I think it's not accurate to use "fossil fuel emissions" here. "Anthropogenic emissions" may be a better term. Many anthropogenic emissions do not originate from fossil fuels, such as VOC emissions from solvent use, NH3 emissions from agricultural activities, and emissions from household biomass fuels.

We have modified the sentence to "Two numerical simulations, both included anthropogenic emissions (mainly fossil fuel emissions) while either with and without the biomass burning emissions (labeled as FFBB and FF, respectively) …"

4. Line 191-193: This is an important point. You may want to show the data in SI.

We have added Fig. S1, the time series of domain-averaged monthly mean $PM_{2.5}$ emissions from FINN and precipitation rate from TRMM dataset, in the supplement.

5. Section 3.1.2: Since fire emissions have a large day-to-day variability, I think the monthly mean AOD may not be suitable for evaluating the model performance. I suggest to use daily product (MOD08_D3) instead. Also, the author argues that the higher simulated AOD than observations is because "a high spatiotemporal resolution in our simulation enables the model to capture episodic fire events better". I think comparing with daily AOD observations could help to confirm whether this argument is true or not.

We appreciate and actually agree on the reviewer's point that fire emissions have a large day-to-day variability. However, due to the frequent appearance of convective systems, MODIS AOD data are often derived based on limited non-cloudy pixels in this region. In this sense, we believe that the comparison of MODIS AOD in a longer period (here we select for monthly) might better serve the purpose. In our pervious study, we have performed more quantitative comparisons of fire pollutants between modeled results and ground-based observations. In Lee et al. (2018), the comparisons of daily PM_{10}, CO, O_3 and visibility have demonstrated that the model is capable to capture episodic fire events during a long-term simulation.

6. Line 303: but smaller number?

The process of cloud droplet collection by rain increases the mass of rain while causes no change to the number of raindrops. We have modified the sentence to "Larger raindrops combining with smaller cloud droplets in FFBB can enhance the efficiency of cloud droplet collection by rain and thus increase rain water mass but cause no change to the number of raindrops, possibly compensating the decrease of rain water mass resulted from a lowered autoconversion."

7. Line 307-308: Why do the mass concentration of snow and graupel increase significantly? Due to the aerosol invigoration effect? You need to explain.

We have added following sentences to explain the change of snow and graupel mass concentration in Lines 335-343 of the revised manuscript:
"Our result is consistent with that of Lin et al. (2006), which suggested that biomass burning aerosols could invigorate convection and then increase precipitation based on satellite observations. The aerosol invigoration effect is referred to such a hypothetic process that increasing number of smaller cloud droplets due to higher aerosol concentration would reduce the efficiency of raindrop formation from self-collection among cloud droplets, and thus further slowdown the loss of these small droplets from being collected by larger raindrops and allow more of them reach high altitudes, where they would eventually collected by ice particles through riming, causing release of latent heat to enhance updraft."

8. Line 317-321, 351-353: Why do the aerosol impacts on stronger and weaker convective systems quite different? You should explain briefly here since the discussions in Sections 3.3 and 3.4 are far away. I think your finding that fire aerosols tend to invigorate weak convection but suppress deep convection is generally consistent with and could be better supported by previous observation-based studies (e.g., Jiang et al., 2018, Nature Communications, DOI 10.1038/s41467-018-06280-4; Zhao et al., 2018, GRL, DOI 10.1002/2018GL077261), which showed that smoke aerosols generally suppress deep convection and convection-generated ice clouds.

We thank the reviewer's suggestion. We have added the following sentences in Lines 396-409 of the revised manuscript:
"Our results show that fire aerosols tend to invigorate weak convection but suppress deep convection in both Sumatra region (r1) and Borneo region (r2). As mentioned before, increasing the number of smaller cloud droplets due to higher aerosol concentration resulted from fire would reduce the efficiency of raindrop formation through the warm-rain processes, thus allowing more cloud droplets reach high altitudes to be eventually collected by ice particles through riming, causing release of latent heat to invigorate updraft while enhancing precipitation through melting of fallen ice particles (Wang, 2005). These processes appear to be more effective to weak convections than deep convections and were in fact well-simulated in the former cases. The results are also consistent with some previous observation-based studies (Jiang et al., 2018; Zhao et al., 2018). Jiang et al. (2018) and Zhao et al. (2018) both concluded that an increase of fire aerosols generally reduces cloud optical thickness of deep convection while Zhao et al. (2018) further showed that fire aerosols tend to invigorate weak convection for small-to-moderate aerosol loadings."

9. Line 381-408: This part is difficult to follow and should be better organized. The author intends to investigate the dependency of the aerosol impact on convective strength (Line 381-382). This question is discussed for r1, but not clearly for r2. From the current text, I am not sure how the aerosol impacts differ for convective systems with different strength in r2. The same problem exists in the conclusion section. Also, why do you introduce daily maximum and *minimum rainfall? A few transitional sentences are needed. Line 391-392: Better to mention clearly that this refers to r1.*

We have made an effort to clarify the commented discussions in Lines 431-448 of the revised manuscript:

"In Sect. 3.2, we have discussed the significant rainfall increase occurred in the weak convective systems after adding fire aerosols due to aerosol invigoration effect. On one hand, regardless the strength of convection, the mean 3-hourly rainfall during the fire periods is 1.06±0.85 mm in FF and 1.09±0.86 mm in FFBB over the Sumatra region (r1), and statistically it does not change significantly in responding to fire aerosols. The rainfall difference in the Borneo region (r2) between FF and FFBB is also insignificant (1.32±1.20 mm $3hrs^{-1}$ in FF versus 1.35±1.14 mm $3hrs^{-1}$ in FFBB). On the other hand, we have found that the impacts of fire aerosols appear in several other rainfall patterns. For instance, the daily maximum and minimum rainfalls display clear differences between the FFBB and FF simulations, specifically in r2 rather than in r1 (Fig. 9). While for r1, the impacts of fire aerosol are reflected in event-wise statistics, e.g., higher event-wise maximum and minimum rainfall intensity in FFBB than in FF, identified in 30 out of 54 convective events in total. These are mostly weak convective events in r1. Interestingly, somewhat opposite to the rainfall statistics in r1, the intensity of event-wise maximum and minimum rainfall in r2 is higher in FF than in FFBB. The daily rainfall peak of 3-hr rainfall in r1 is mostly less than 3 mm; in comparison, one-third of convective events in r2 have daily maximum 3-hr rainfall exceeding 3 mm (Fig. 9c), suggesting that the convective systems in r2 tend to develop stronger than in r1 and the fire aerosols significantly suppress the maximum rainfall intensity of strong convections in r1. …"

10. Figures 5, 6: Some texts in the figures are too small to be visible.

Texts in the figures have been modified in the revised manuscript.

Reference:

Jiang, J.H. *et al.*, Contrasting effects on deep convective clouds by different types of aerosols, *Nature Communications* **9**(2018), p. 3874.

Lee, H.-H. *et al.*, Impacts of air pollutants from fire and non-fire emissions on the regional air quality in Southeast Asia, *Atmos. Chem. Phys.* **18**(2018), pp. 6141-6156.

Lin, J.C., Matsui, T., Pielke Sr., R.A., Kummerow, C., Effects of biomass-burning-derived aerosols on precipitation and clouds in the Amazon Basin: a satellite-based empirical study, *Journal of Geophysical Research: Atmospheres* **111**(2006).

Shi, H. *et al.*, Modeling Study of the Air Quality Impact of Record-Breaking Southern California Wildfires in December 2017, *Journal of Geophysical Research: Atmospheres* **124**(2019), pp. 6554-6570.

Wang, C., A modeling study of the response of tropical deep convection to the increase of cloud condensation nuclei concentration: 1. Dynamics and microphysics, *Journal of Geophysical Research: Atmospheres* **110**(2005), p. D21211.

Zhao, B. *et al.*, Type-Dependent Responses of Ice Cloud Properties to Aerosols From Satellite Retrievals, *Geophysical Research Letters* **45**(2018), pp. 3297-3306.