Interactive comment on "Aerosol and dynamic effects on the formation and evolution of pyro-clouds" by D. Chang et al.
MS No.: acp-2014-61

Dear Reviewer,

We would like to thank you for the valuable and constructive comments/suggestions on our manuscript. We have revised the manuscript accordingly and please find our point-to-point responses below (line numbers refer to the new version of manuscript). In addition, the title of the manuscript is revised to be "Regime dependence of aerosol effects on the formation and evolution of pyro-convective clouds".

Anonymous Referee #3

This paper reports on results of 1000s of 2D aerosol-cloud model simulations to study the impact of aerosols on a pyro-convective cloud under various aerosol and dynamical conditions. The quality of the work is very good because it provides a parameter space explaining where to expect clouds to be sensitive to aerosol effects and what conditions are not conducive to aerosol effects. The first half of the paper is well written. It was a pleasure to read. However, the discussion of the results became quite confusing. There were not good interpretations of the results. The study is limited to the 2D framework, and may be even more limited to certain environmental conditions (T, RH, and wind profiles). The limitations of the present study and the interpretation of results must be discussed more fully before publishing the paper.

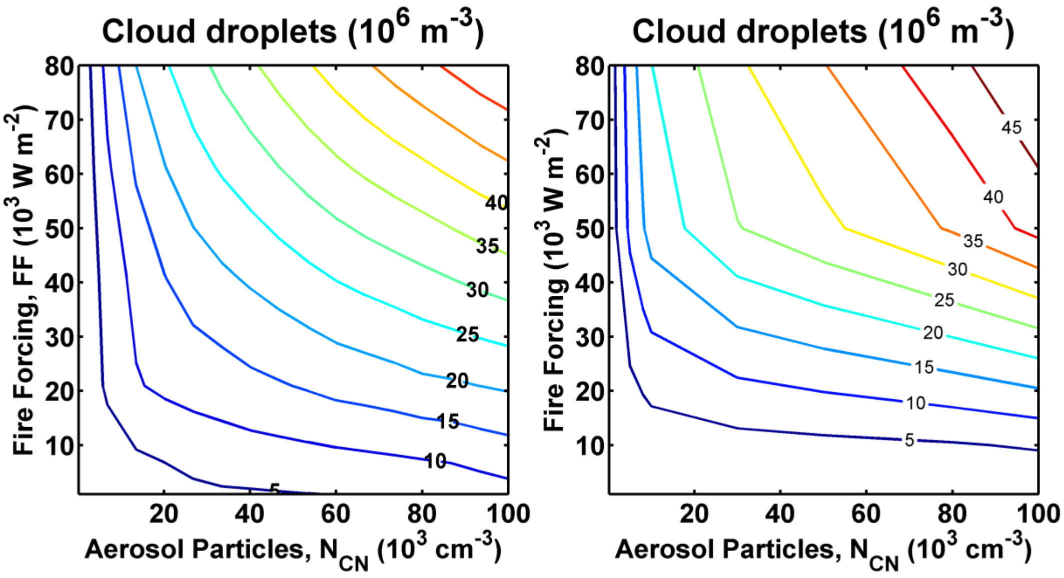
Response: We appreciate the comments very much. Within this work, we aim to investigate the sensitivity of the pyro-convective clouds to a wide range of aerosol concentrations under different updraft conditions. We have revised and extended the discussion of the results. Especially, a new approach has been adopted in which the spatial and time-resolved contribution of individual processes has been visualized for the interpretation of the results. With similar approach, we are also able to show the integrated process rates for all the studied cases, not only the four individual cases. Please see Figs. 16, 18 and 20 for the process analysis of cloud droplets, raindrops and frozen water content respectively, and the corresponding text is in Sect. 3.3. The relative importance of each microphysical process is evaluated and discussed in Sect. 3.3.4. The ATHAM model consists of several tens of microphysical processes. By identifying the contribution from individual processes, PA may also provide an opportunity for the simplification of microphysical schemes. For example, out of 24 microphysical processes that are directly related to the budget of liquid droplets, over 90% of the mass and number changes are contributed by only 10 processes.

We agree with the referee about the limitations and have emphasized that caveats are required in the interpretation of our results. Besides, we have performed complimentary 3-D simulations to illustrate such potential problem as in the supplementary material.

Major comments:

While it makes sense to do 2D simulations in order to conduct 1000s of simulations, the ability of the 2D simulations should be evaluated with a comparison of results to a 3D simulation. This has been common practice in many past cloud modeling studies.

Response: We agree. In the revised manuscript, we run a series of complimentary 3-D simulations (~100 cases), and the discussion concerning the 3-D results (cloud droplets, raindrops, frozen water content, and precipitation) have been included in the supplementary material. Take cloud droplets for example, the regime dependence from the 3-D simulations (Fig. R1b) looks similar to the 2-D results (Fig. R1a) though the absolute dependency may vary. This implies that the use of such regime dependence requires caveats because it may differ for different model dimensionality (2D vs. 3D). In the main text, we have included more discussion concerning these uncertainties: “In this study, we demonstrate the performance of ensemble simulations in determining the regime dependence of aerosol effects. The use of such regime dependence requires caveats because it may differ for different cloud types, aerosol properties, meteorological conditions and model configurations (e.g., microphysical schemes, dynamic schemes, dimensionality, etc.; the 3-D results are in the supplementary material)”. Please see Lines 739-743.



(a) (b)

Figure R1. Number concentration of cloud droplets calculated as a function of aerosol number concentration (N_{CN}) and updraft velocity (represented by FF) from 2-D (a) and 3-D (b) simulations.

I recommend including all the supplementary material in the main manuscript. I found the supplementary figures relevant to the discussion and quite interesting. I also recommend removing the normalized number and mass concentrations (Fig 2c-f, Fig 4c-f, Fig 6c-f, and Fig 8b-c) and replacing them with the relative sensitivity plots in Figures 3, 5, 7, and 9. Better yet, would be to just remove the former and keep the relative sensitivity plots in separate figures.

Response: Accepted. We have moved all the tables and figures in the supplementary to the main text, and replaced the figures for the normalized concentrations of each hydrometeor with the relative sensitivity plots. Please see Figs. 7, 9, 12 and 13 in the revised manuscript.

I believe the intended audience is the aerosol-cloud community, and not necessarily the pyro-cumulus community. The cloud community is much more concerned about updraft speeds than the forcing of the convective updrafts. Thus, I strongly recommend that the approximate updraft strength (maximum vertical velocity is a good measure) be given along with the fire forcing values as another axis in the plots. The readers would then be able to put this paper's results in context of their knowledge of convective storms.

Response: Accepted. The relationship between fire forcing and the corresponding updraft velocities is given in Sect. 2.2, which is logarithmic. Thus we add the maximum vertical velocity along with the fire forcing as the second y axis in the contour plot for the number concentration of cloud droplets (Fig. R2, which is Fig. 7a in the new manuscript).

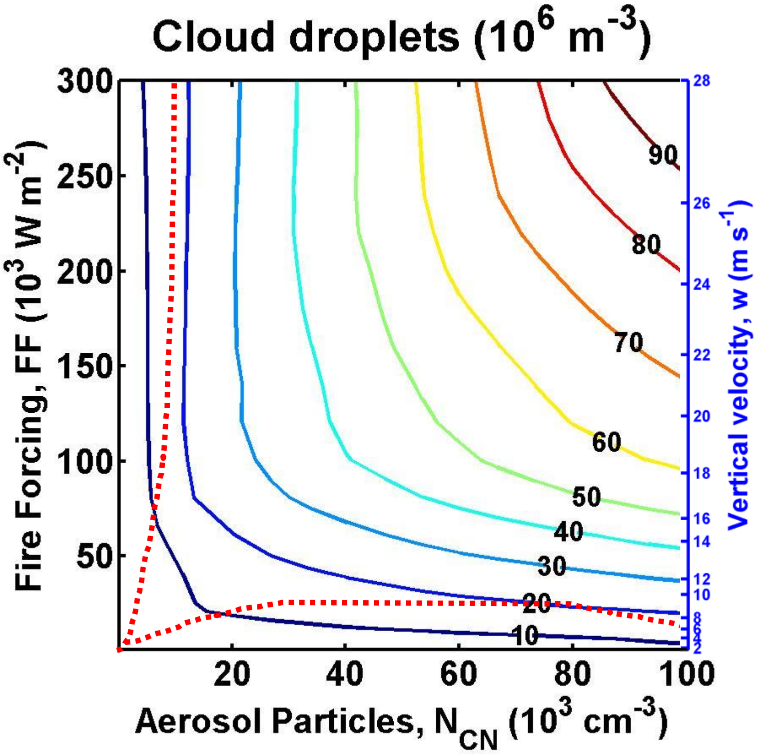


Figure R2. Number concentration of cloud droplets calculated as a function of aerosol number concentration (N_{CN}) and updraft velocity (represented by FF).

The results presented in sections 3.2 and 3.3 are quite complicated. I would recommend introducing the results in a simpler manner before Figure 2 is discussed. My suggestion would be to show an instantaneous cross-section of the cloud for the LULA, LUHA, HU-LA, and HUHA cases. The cloud could be color coded by droplet number concentration or cloud mass concentration (or cloud and rain mass concentration). This type of figure would allow the reader to see a figure of something they are familiar with, and allow the authors to introduce the more complicated subsequent figures (Figures 2-9).

Response: Accepted. In Sect. 3.2 of the revised manuscript, we put the time evolution of horizontally-averaged concentration of each hydrometeor for four extreme cases in the beginning of the result part. After briefly introducing the temporal and spatial distribution of each hydrometeor, their dependence on the aerosol and fire forcing would be presented. For the temporal and spatial distribution of cloud droplets, please see Lines 244-250:"Figure 6 shows the temporal evolution of horizontally-averaged mass concentration of cloud droplets (M_{CD}) under the four pairs of FF and N_{CN} conditions. Under weak fire forcing conditions (LU), the formation of cloud droplets usually occurs from 20 min, and concentrates at an altitude of 4-7 km. The duration of cloud droplets usually last for a short period (40~60 min). Under strong fire forcing conditions (HU), the cloud droplets form earlier (around 5 min), and most cloud droplets are located at a height of 5-9 km. Besides, the cloud droplets reach steady state because of the cycling of cloud formation."

For raindrops, please see Lines 303-307:"Figure 8 exhibits the temporal evolution of the horizontally-integrated mass concentration of raindrops under four different conditions. Compared with cloud droplets (Fig. 6), the occurrence of raindrops is much later, especially when N_{CN} and fire forcing are in a high level. Only for LULA case, numerous raindrops can be found in a high altitude (5-7 km), while for other cases, most of raindrops are located below 5 km (~0 ℃)."

For frozen particles, please see Lines 334-340: "The time evolution of frozen water content in Fig. 10 suggests that the formation of frozen water content usually occurs in a high level (5-9 km for LU case, and 7-13 km for HU case), and the height of base layer and top layer decreases as time goes by. Under LU condition, the appearance of frozen water content is around 35 min, and lasts for ~120 min, with the peak concentration around 50~70 min. Under HU condition, the frozen particles form around 10 min, and keep in a steady state."

The main reason the results become difficult to understand is because a lot of jargon is used, and the authors mostly describe what is shown in the figure, but don't do a very good job of interpreting what the figure says. For example, instead of saying "FF exhibits positive effects on raindrop formation", it could be written like, "as the fire forcing (or updrafts) increases in magnitude, the amount of rain increases (Figure 4b), but the size of rain drops vary because of the complex behavior of the response of the rain drop number with fire forcing (Figure 4a)". The other reason the results are difficult to comprehend is that the text jumps from one figure to another in a single sentence. Some of this jumping would be reduced by putting the relative sensitivity plots in the same figure as the contour plots (as a function of aerosol number concentration and fire forcing).

Response: Thanks for the constructive suggestions. In the revised manuscript, we optimized the formulation and reduce the use of jargon. To make the transition of discussion smoother and easier to comprehend, we move the relative sensitivity plots in the same figure as the contour plots. For raindrops, we have modified the text, and please see lines 315-325. "As *FF* increases in magnitude, the amount of rain produced (M_{RD}) increases (Fig. 9b), but the size of raindrops varies because of the complex behavior of the response of the rain drop number (N_{RD}) to *FF* (Fig. 9a). The aerosol effect is non-monotonic: M_{RD} increases with aerosols in the lower range of N_{CN} values (<~1000 cm^{-3}), but further increases in N_{CN} result in a decrease in M_{RD}. Combining with the relative sensitivities (Figs. 9e, and 9f), the influence of *FF* is much more significant than that of N_{CN} in most cases. For example, the upper left corner (an aerosol-limited regime for N_{CD}) becomes a transitional regime for M_{RD} with RS (FF) of 0.1 and RS (N_{CN}) of -0.06 (Fig. 9). High sensitivities of M_{RD} to N_{CN} are found at low N_{CN} conditions, but the sensitivity decreases as N_{CN} increases

(Fig. 9e). The N_{CN} plays the most negative role in M_{RD} under intermediate N_{CN} conditions (N_{CN} of several 1000 cm^{-3}).” For frozen particles, instead of “The FF and N_{CN} show positive effects for both the number and mass concentrations of the”, it is written to be “With the enhancement in FF and N_{CN}, both the number and mass concentrations of the frozen water particles (N_{FP} and M_{FP}, respectively) increase”. Please see Lines 365-366. For other hydrometeors, the language description in the discussion part is also modified to avoid the use of jargon.

Specific comments:

1. p. 7784, line12. Are the aerosols distributed uniformly in the vertical direction too? What are the initial horizontal winds? Do initial horizontal winds vary with height? That is, is there any vertical wind shear? (Fan et al., 2009 show how aerosol-cloud-precipitation results vary with vertical wind shear)

Response: (1) The concentration of ambient aerosols is set to be homogeneous over the modeling domain, without considering the spatial and temporal distributions of atmospheric aerosols during the simulations, which is similar to some previous studies (Seifert et al., 2012; Reutter et al., 2013). We admit the variability of aerosols during the simulation is ignored and may leads to a bias compared to a real fire (Wang et al., 2013). We add this discussion about the bias in the revised manuscript; please see lines 152-156. For the future research, we will try to improve the representation of the aerosol particles and take into account the full complexity of all chemistry-aerosol-cloud interactions.

(2) Within our 2-D simulations, the initial horizontal wind was set to be zero, and therefore there is no vertical wind shear. We admit further work is still needed to investigate the wind shear impact on the convection strength as suggested in Fan et al. (2009), which is for now beyond the scope of this manuscript. Therefore, we add some brief discussion in Sect 3.1 of the main text, which is “Finally, we note that the horizontal wind shear can also affect the convection strength (Fan et al., 2009), which could be investigated in detail in future studies.” Please see Lines 231-232.

2. p. 7785, line 20. As it is spring convection season here in the United States, it is important to note that severe convection has updrafts much greater than 20 m/s. Severe convection also transports much more mass to the upper troposphere and delivers more precipitation to the surface than the smaller storms found over the U.S. Thus, I recommend saying that the updrafts simulated represent those found in air mass thunderstorms or trade wind cumulus.

Response: Accepted. We revised this sentence to be "In pyro-convective clouds, the updraft velocities range from ca. 0.25 to 20 m s^{-1} (Reutter et al., 2009), which represent the range found in trade wind cumulus to thunderstorms (Pruppacher and Klett, 1997)." Please see lines 206-209.

3. p. 7787, lines 3-24. I was confused as to why Figure 2 was introduced here, but not explicitly discussed before Figure 3 was discussed on line 20. Here is an example of why I think Figure 3 should replace Figure 2c-f.

Response: In the revised manuscript, we have changed the figure arrangement. Please see Figs. 7, 9, 12 and 13 in the revised manuscript.

4. p. 7787, lines 21-24. Can you show how the cloud system buffering effect is affecting the droplet number concentration? I thought this study was modeling a single convective storm (p. 7782, line 4) and therefore do not see a cloud system effect for this study. A better explanation is needed.

Response: It is true that this work focused on the aerosol effect on the isolated pyro-convective clouds. We have modified the text to be: "The reduced sensitivity of cloud droplets to aerosols can be explained by the buffering effect of the cloud microphysics, so that the response of the cloud system to aerosols is much smaller than would have been expected." Please see Lines 283-286. The explanation can be "Under weak updrafts, the $N_{\mathrm{CD}}/N_{\mathrm{CN}}$ ratio is sensitive to ambient supersaturations. In this case, a larger supersaturation induced by stronger updrafts can effectively change the $N_{\mathrm{CD}}/N_{\mathrm{CN}}$ ratio and thus N_{CD} is sensitive to the updraft velocity. On the other hand, the stronger dependence of $N_{\mathrm{CD}}/N_{\mathrm{CN}}$ on the supersaturation also changes the role of aerosols. As more aerosols reduce supersaturation, increasing N_{CN} tends to reduce the activated fraction, $N_{\mathrm{CD}}/N_{\mathrm{CN}}$. Taking N_{CN} = 60,000 cm^{-3} (FF = 2,000 W m^{-2}), for example, a 10% increase in N_{CN} causes a 4% decrease in $N_{\mathrm{CD}}/N_{\mathrm{CN}}$, whereas a 10% decrease in N_{CN} leads to an 8% increase in $N_{\mathrm{CD}}/N_{\mathrm{CN}}$. The impact of changing N_{CN} on the $N_{\mathrm{CD}}/N_{\mathrm{CN}}$ ratio counteracts partly or mostly the positive effect of N_{CN} on cloud droplet formation. " Please see Sect. 3.3.1 (Lines 442-450).

5. p. 7789. Perhaps it is because I am used to U.S. convective storms where hail is common, but why is there no hail in 3 of the 4 cases shown in Figure S4? Hail is only in the LULA case, which does not make sense since hail is associated with high updrafts. I am concerned about the worthiness of these results.

Response: Actually the absolute concentration of hail generally increases with the enhancement in the fire forcing, as displayed in Fig. R3, although there is some deviations. But compared to other hydrometeors, its contribution is not important. Thus from Fig. 11 in revised manuscript, it seems the relative percentage of hail is very low. We add some discussion in the main text, which are "It is worth noting that stronger *FF* leads to increasing absolute concentration of hail. But compared to other hydrometeors, its contribution is not important and the relative percentage is very low." Please see Lines 361-363.

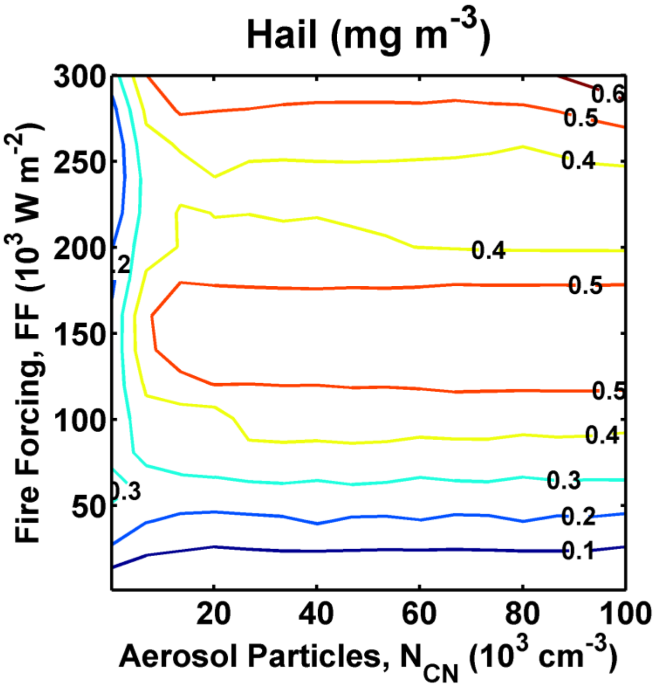


Figure R3. Mass concentration of hail calculated as a function of aerosol number concentration (N_{CN}) and updraft velocity (represented by FF).

6. p. 7789. I am also surprised that the primary loss of cloud water to any of the ice hydrometeors is through cloud drop freezing. Does this mean that cloud drops do not transfer to the ice hydrometeors until they are at temperatures < -40 C? In my past work (albeit, with microphysics not quite as sophisticated as that presented here), the most common way for cloud drops to freeze was through the riming process, especially snow accreting cloud drops, or graupel accreting cloud drops.

Response: The cloud drop freezing is a primary loss of cloud water concerning the budget of ice particle number. For the mass budget from cloud water to ice hydrometeors, the major path way is the Wegener-Bergeron-Findeisen (WBF) process. The evaporation of small cloud droplets (*cep*) provides more water vapor, leading to a higher supersaturation with respect to ice and enhanced growth of ice embryos by vapor deposition (*vdi*). At the same time, the consumption of water vapor could reduce the water saturation, thereby further boosting the evaporation of cloud droplets. The other freezing processes (e.g., riming of cloud droplets to snow, graupel and hail) also take place, but their contribution is relatively small within our ATHAM modeling results. The contribution of cloud freezing to the mass budget become comparable to WBF process only at extremely high updraft (*FF*>10^5 W m^{-2}).

7. p. 7790, lines 8-14. Why does the rain rate (Figure 8a) behave so differently from rain mass concentration (Figure 4b)?

Response: In the old version of manuscript, the contour plots for raindrops are smoothed, while the rainfall contour plot is not smoothed. In the revised version, we replot the contour plots for raindrops based on the original data, and found the isolines of the rain water content (Fig. R4, which is Fig. 9b in revised manuscript) behave similar with the rain rate (Fig. 13a in the revised manuscript).

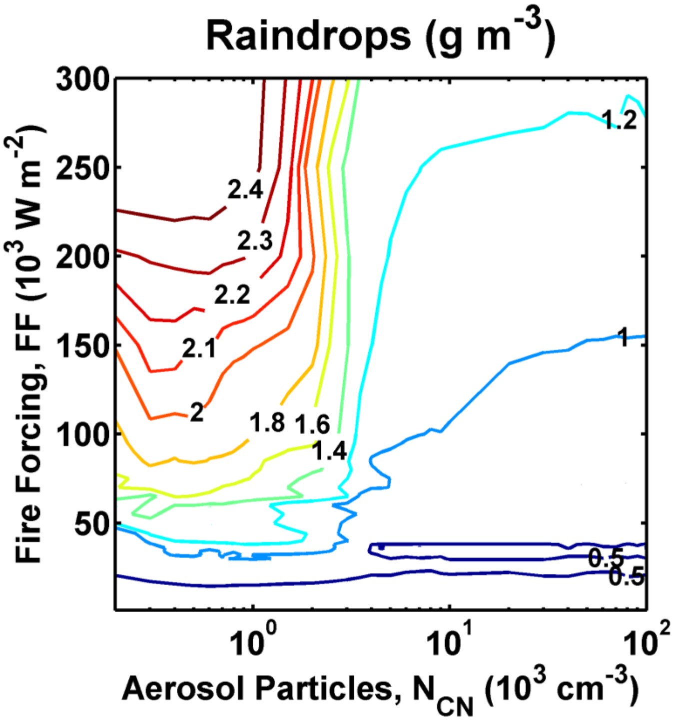


Figure R4. Mass concentration raindrops calculated as a function of aerosol number concentration (N_{CN}) and updraft velocity (represented by *FF*).

8. p. 7790, lines 19-20, Could the authors please clarify where these precipitation-enhanced and suppressed regimes are on the figure?

<u>Response:</u> We make clear of the definition of the regimes for precipitation, which can be found in Lines 384-387: "In the precipitation-invigorated regime (N_{CN} < ~1000 cm^{-3}), an increase in N_{CN} leads to the increase in the precipitation rate, and reduction in RS (N_{CN}) (Fig. 13b). In the precipitation-inhibited regime (N_{CN} > ~1000 cm^{-3}), aerosols start to reduce the precipitation, which is reflected in a negative $RS(N_{\mathrm{CN}})$." Besides, these two regimes are also marked in the figure (Fig. R5, which is Fig. 13a in the revised manuscript).

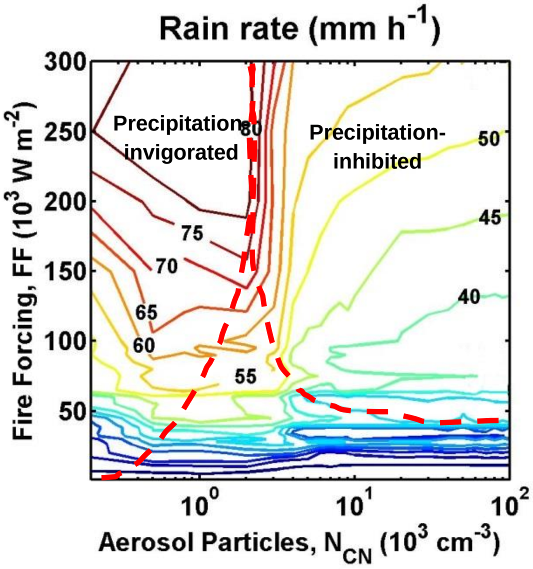


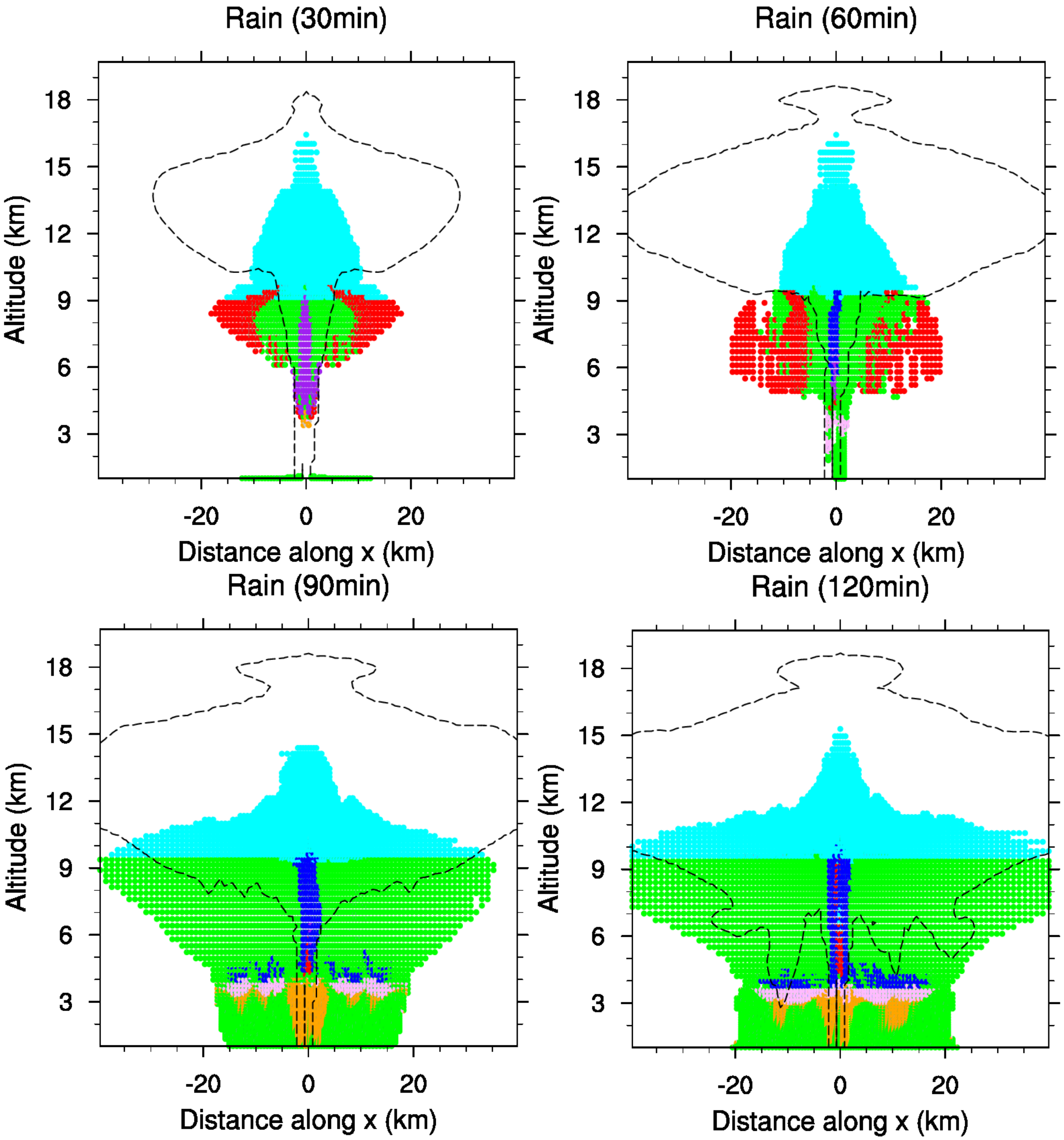
Figure R5. Contour plot of rain rate calculated as a function of aerosol number concentration (N_{CN}) and updraft velocity (represented by FF).

9. p. 7792, lines 4-8. At what updraft speeds does the change in updraft speed not significantly influence the N_{CD} to N_{CN} ratio?

<u>Response:</u> Within our model, the cloud nucleation (CCN activation) process is based on the lookup table derived from parcel model simulations for pyro-convective clouds (Reutter et al., 2009). It is observed that for pyro-convective clouds with high aerosol concentration (>10^4 cm^{-3}), when the updraft velocity is above 15 m s^{-1}, the N_{CD} to N_{CN} ratio is 0.9 (Reutter et al., 2009), and the further increase in fire forcing does not largely change N_{CD} to N_{CN} ratio. We also include this threshold value in the main text. Please see line 438-439.

10. Section 3.3, While these results are interesting and useful, I was wondering if there is anything interesting in the time evolution of these microphysics processes. Are the relative contributions of the different processes shown in the figures hold true at different times in the simulation?

Response: Thanks for the stimulating suggestions. We plotted the contribution of the microphysical processes in each modeling grid under different simulation period. Here we take raindrops under HUHA condition (w = 27 m s^{-1}; N_{CN}=100,000 cm^{-3}) for example (Fig. R6). Each plot shows the vertical cross sections of the averaged change rate of main processes contributing to raindrops over 30 simulation minutes. Colors within each pie chart reflect the percentage of processes in each grid. As mentioned in the main text, the warm rain process is quite unimportant under strong *FF* condition. However, it is observed from Fig. R6 that the warm rain process is the leading source of raindrops at the beginning stage (60 min). The size of the raindrops formed from autoconversion and accretion is relatively small, which can easily evaporate. The melting of frozen particles to form raindrops becomes more significant after ~90 min, which dominates the production of raindrops. As shown in Fig. R6, although the processes still continue at 180 simulation minutes, the microphysics has already fully developed during this simulation period. Thus our 3 simulation hour could cover the characteristics of the formation and evolution of the pyro-convective clouds.


Rain (30min)
Rain (60min)
Rain (90min)
Rain (120min)
Altitude (km)
3
6
9
12
15
18
-20
0
20
Distance along x (km)

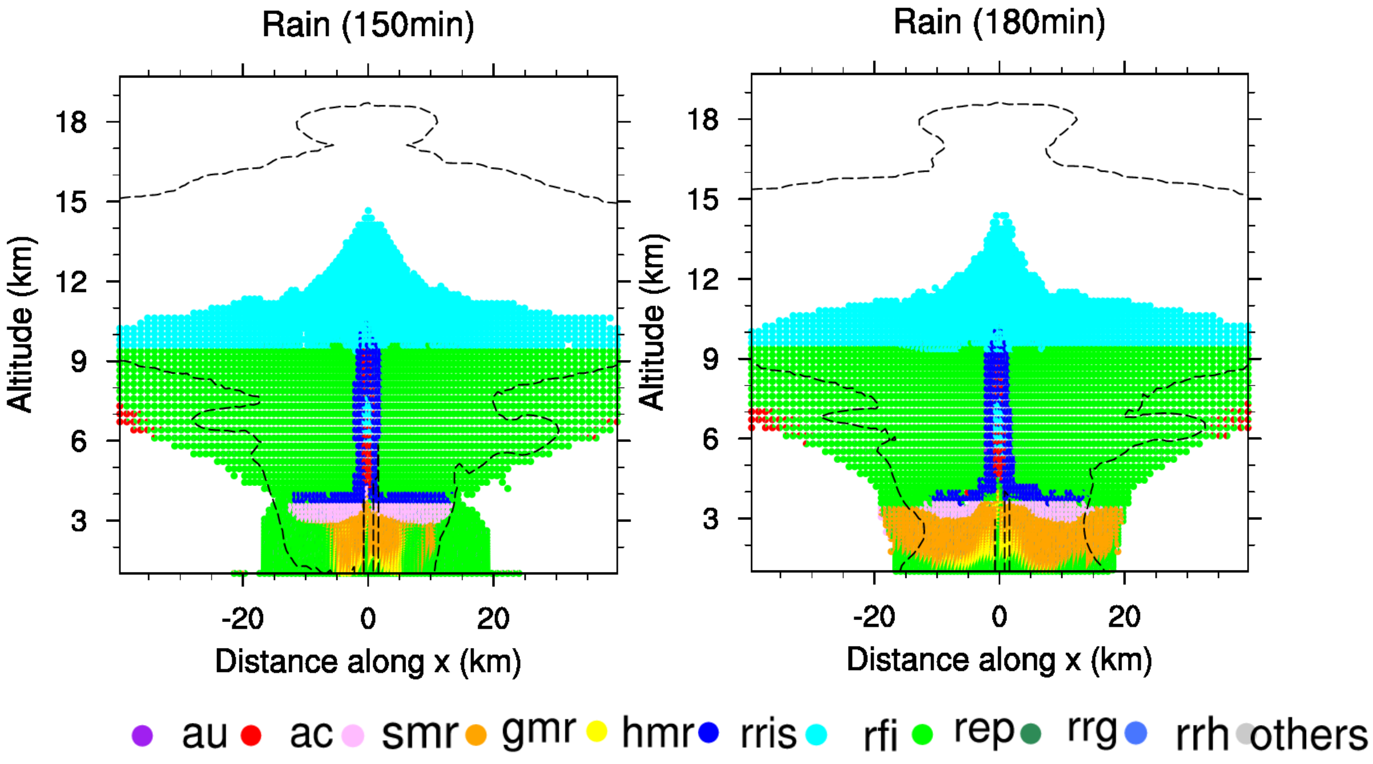


Figure R6. The pie charts summarize the vertical cross sections of the change rate of main microphysical processes contributing to raindrops. Each pie chart shows the averaged contribution over the past 30 min. Colors within each pie chart reflect the percentage of processes in each grid. The black dashed line is the 0.1 μg kg^{-1} isoline of the interstitial aerosol, indicating the shape of smoke plume. Warm colors denote the source, while cold colors denote the sink. The acronyms indicate au: autoconversion; ac: accretion; s/g/hmr: melting of snow/graupel/hail to form raindrops; rris: riming of raindrops to form ice and snow; rfi: freezing of raindrops to form ice crystals; rep: raindrop evaporation; rrg/h: riming of raindrops to form graupel/hail.

For other hydrometeors, please see the revised manuscript (sect. 3.3.1 for cloud droplets, sect. 3.3.2 for raindrops, and sect. 3.3.3 for frozen particles).

11. Section 4, Conclusions. I recommend removing the jargon for those people who just read the conclusions. Explaining the meaning of the results to our understanding of the aerosol-cloud science would be a bonus.

Response: In the new manuscript, we have modified the conclusion part, and reduced the jargon to avoid difficult comprehension. Instead of saying "positive/negative effect", we explain our results in a simple and understandable way. For example, instead of "Larger FF resulted in more precipitation, whereas the effect of aerosols on precipitation was complex and could be either positive or negative" in conclusion 4. The conclusion concerning precipitation is changed to be as follows with detailed explanation: "Larger *FF* resulted in more precipitation, whereas the effect of aerosols on precipitation was complex and could either enhance or suppress the production of precipitation. The suppression on the precipitation is due to the change in the fraction of small frozen particles and total melting rate of frozen particles. The enhancement on the precipitation resulting from increasing N_{CN} under low aerosol condition is a result of changes in the vertical distribution of frozen particles and its evaporation process." Please see 687-692. For other conclusions, we have also revised the language description to avoid the use of jargon.

In addition to interpreting the meaning of the results, we have also described the present limitations of this work and have emphasized that caveats are required in the interpretation of our results.

12. p. 7796, lines 5-12. Isn't conclusion 1 a conclusion of Reutter et al. (2009)? I'm not sure it needs to be repeated here.

Response: Conclusion 1 is the result of the deterministic regimes from our simulations, which consider full microphysics and the larger temporal and spatial scales of a single pyro-convective cloud. Here we intended to emphasize that even when we consider a larger scale for pyro-convective clouds, three-regime structure for the number concentration of cloud droplets still exists.

13. p. 7796, lines 26-27. Conclusion 4 reports a result, but does not explain why it happens. An explanation should be included.

<u>Response:</u> We run more simulations and conduct more analysis to explain Conclusion 4, and add the explanation in the Conclusion part. The text is "(4) Larger FF resulted in more precipitation, whereas the effect of aerosols on precipitation was complex and could be either positive or negative. The negative aerosol effect is due to the change in the fraction of small frozen particles and total melting rate of frozen particles. The positive effect of aerosols under low aerosol condition is a result of changes in the vertical distribution of frozen particles and its evaporation process." Please see lines 687-692.

Technical comments:

p. 7782, line 25. Do the authors mean "soil processes"?

<u>Response:</u> It is the "soil module" inside the ATHAM model, which is not included in our modeling configuration and thus we did not explain it in detail. We make it clear in the main text. Please see line 109.

p. 7785, line 12-13. It may be better to say, "summarizes all the microphysical processes and their acronyms"

<u>Response:</u> Accepted. This sentence is revised to be "Table A1 summarizes all the microphysical processes and their acronyms." Please see lines 190-191.

p. 7787-7790, please state what aerosol and FF (updraft speeds) values constitute the low and high aerosol cases and the low and high updraft cases.

<u>Response:</u> Actually we stated the range of low/high aerosol and *FF* conditions in the figure captions, and the text is "Note that the low/high aerosol and fire forcing conditions (LA, HA, LU, and HU) in these figures refer to a group of N_{CN}/FF conditions. LU: low updrafts (1,000–7,000 W m^{-2}); HU: high updrafts (75,000–300,000 W m^{-2}); LA: low aerosols (200–1,500 cm^{-3}); HA: high aerosols (10,000–100,000 cm^{-3}).” To make clear of this, we will also add this statement in the main text. Please see lines 276-280.

Figures 2-15, please label individual panels. This can easily be done as part of the panel title.

Response: Accepted. We label each panel in the figures.

p. 7789, line 25. It seems like Rosenfeld’s Science paper should be cited here.

Response: Accepted. Rosenfeld et al. (2008) described how the deep convective clouds evolve when more polluted aerosol particles are added in the atmosphere based on the conceptual model. We cite this paper in Line 353-354.

p. 7790, line 10. The Tao et al. Geophys. Res. (2012) review would be very good to cite here. Tao, W.-K., J.-P. Chen, Z. Li, C. Wang, and C. Zhang (2012), Impact of aerosols on convective clouds and precipitation, Rev. Geophys., 50, RG2001, doi:10.1029/2011RG000369.

Response: Accepted. Tao et al. (2012) summarized the aerosol effects on the CCN activation, warm-rain process, mixed-phase clouds, and precipitation in terms of microphysical scale, cloud-resolving scale, and regional scale, which are retrieved from the theoretical analysis, observations, and numerical modeling. The underlying mechanisms and the comparison between the results from different studies was also presented and analyzed. We add this citation in this part. Please see line 377.

p. 7793, line 21. To be consistent, write “rain drops” instead of droplets

Response: Accepted. Please see line 500.

p. 7793, line 22. Should be melted snow (singular)

Response: Accepted. We corrected this word. Please see line 499.

p. 7798, line 14. It may be good to cite Van den Heever and Cotton's work here. I think they were the first to show the aerosol-cloud-precipitation effects at longer time scales (> 12 hours).

Response: Accepted. We have included the Van Den Heever and Cotton (J Appl Meteorol Clim., 2007) for reference here. Please see Line 746.

Figure S2. Could this figure be shown on a skew-T plot and have the horizontal winds included? It may also be useful to show how big of a temperature increase occurs as the fire forcing increases.

Response: (1) The atmospheric radiosonde for the simulations is shown in Fig. R7 by a skewT-logp diagram, which has been included as the new Fig. 2 in the revised manuscript.

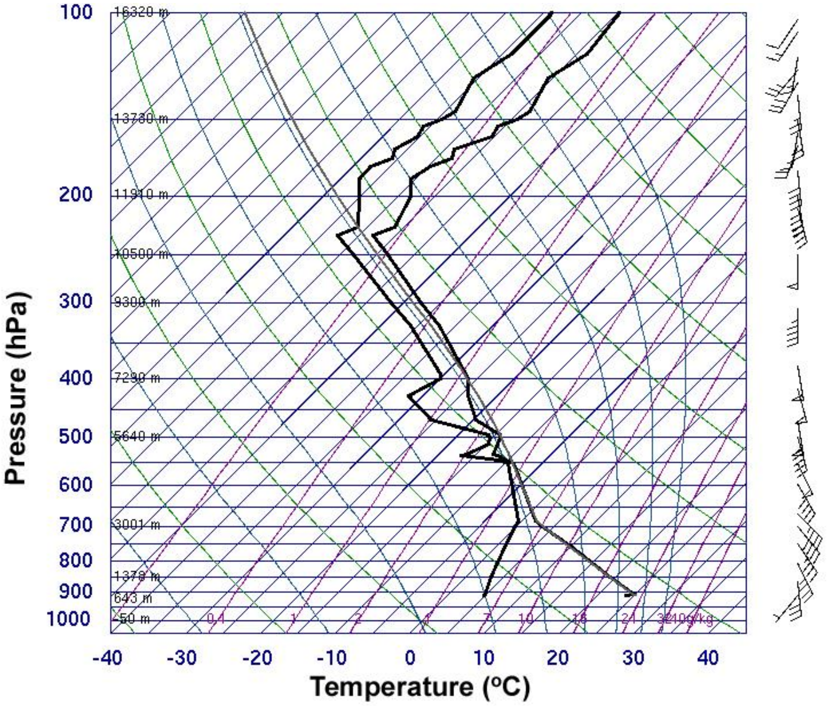


Figure R7. Atmospheric sounding launched near Edmonton, Alberta on 29 May 2001. The right black line represents the temperature, and the left black line corresponds the dew-point temperature. This weather information is from the University of Wyoming Department of Atmospheric Science (http://weather.uwyo.edu/).

(2) We plotted the relationship between fire forcing and the corresponding maximum temperature at cloud base under different aerosol conditions. As the aerosol impact on the temperature is very small, we take N_{CN}=5,000 cm^{-3} for example. The correlation of fire forcing and temperature is shown in Fig. R8. The shaded area indicates the variability of estimation over each simulation period. According to the figure, the temperature at cloud base varies monotonically from 7.6 to 16.4 ℃ as fire forcing increases from 1×10^3 to 3×10^5 W m^{-2}. We have included this discussion in Sect. 3.1. Please see Lines 221-230.

In the discussion section (Sect. 3.2.1), we have added the temperature as the secondary vertical axis in the contour plot for cloud mass concentration for reference (Fig. R9, which is Fig. 7b in the revised manuscript).

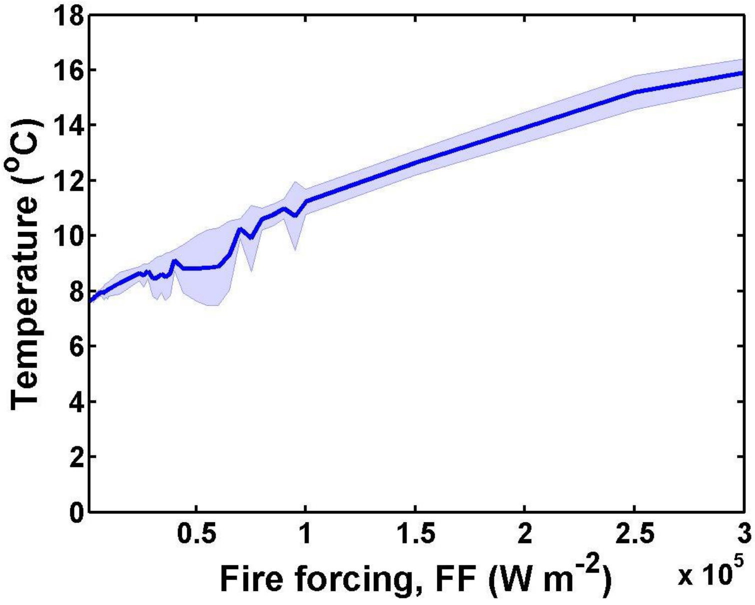


Figure R8. The correlation of fire forcing and the corresponding maximum temperature at cloud base. The shaded area indicates the variability of estimation (±½σ) over each simulation period.

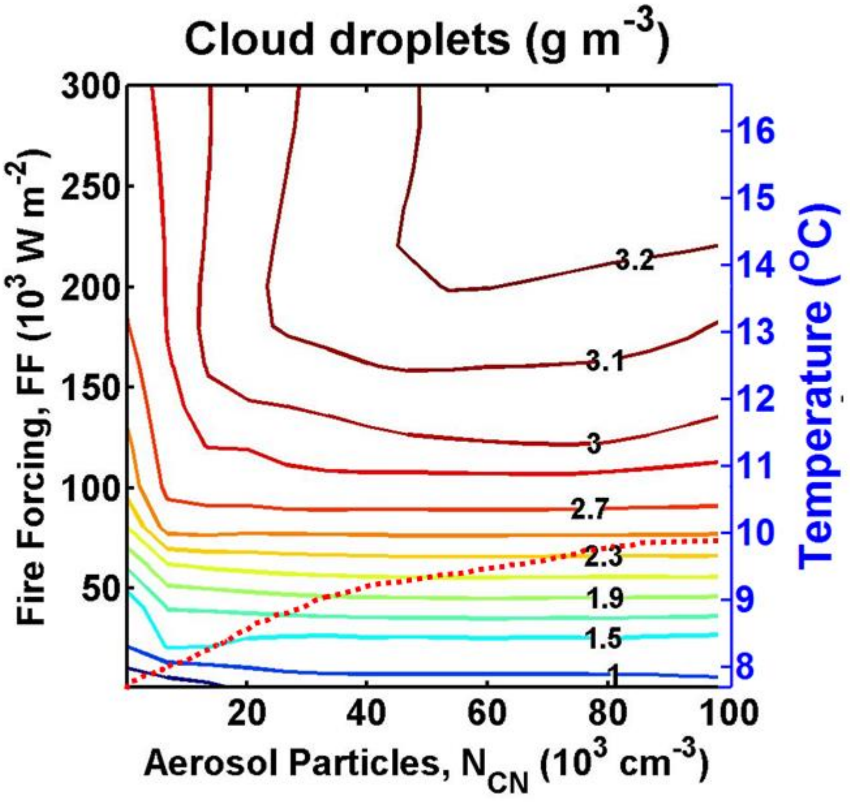


Figure R9. Mass concentration of cloud droplets calculated as a function of aerosol number concentration (N_{CN}) and updraft velocity (represented by FF).

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