Anonymous referee #1: RC1

With WRF simulations, this study investigates the aerosol impacts on pristine continental convective precipitation over Naqu, China. It is found that under relatively polluted conditions, the onset of precipitation is delayed with increased cold rain intensity. The finding is interesting and worthy for publication.

Thank you very much for your constructive comments and suggestions. Our point-by-point replies are given as below, and the corresponding revisions are made in the previous manuscript. **Line number below refers to the clean version**, while changes are tracked in the tracked version.

In this study, different amount of aerosols have been considered and analyzed, I wonder if the surface topography (particularly TP region) along with aerosol types could play a role and analysis of these effects could be highly valuable. Of course, considering the focus of this study, these aspects could also be done in future by simply stating them in the final section.

Response:
In terms of topography, the area around Naqu is almost a flat terrain with an altitude of over 4,000 meters and a simple surface type, which is meadow. There are only small hills to the east side of Naqu. Cheng et al., (2022) carried out the sensitivity experiments including removal the hills to the east of Naqu, and found that the existing of hills to the east of Naqu enhanced the convection by increasing the low-level wind convergence. In terms of aerosol types, the main aerosol types on the Tibetan Plateau were further identified as continental background, biomass burning, and dust (Pokharel et al., 2019; Yang et al., 2021; Zhu et al., 2019; Zhao et al., 2020). (Line 91-93) Based on the input data from MERRA-2, three species of aerosols are calculated as water-friendly aerosols, which are sea salt, sulfate, and organic carbon. Among them, organic carbon aerosols dominate in Naqu on 23 July 2014. Dust particles larger than 0.5 μm are ice-friendly aerosols in model.

We agree that the surface topography (particularly TP region) along with aerosol types could play a role in precipitation. However, the focus of this article is to analyze the effect of changes in condensation nucleus number concentration on precipitation microphysical processes, so the aerosol species along with the topography were not analyzed in detail. We think it would be better to mention it in final section to make the discussion more comprehensive. Therefore, we added one sentence stating that in the discussion part. "More factors, such as latent heat, sensible heat, surface topography, aerosol types, etc. should be carried out as comprehensive analysis in this region." Line 431-432

Line 50, "Due to"

Response: It has been revised. Line 51

Line 50-52, Ma et al. (2018, doi: 10.1002/2017MS001234) might be able to serve as a support for this claim.

Response: It has been added. Line 51-53

Line 54-57 and 88-90, A recent three-pole (Arctic, Antarctic and TP) aerosol characteristics study shows the aerosol type comparison results, including the aerosol types and sources over the TP, which is worthy to mention, Yang et al. (2021, doi: 10.5194/acp-21-4849-2021).

Response: It has been added and revised. Line 55-58 and Line 90-93

Line 66-67, This is true, while adding the reason could be more appreciated, such as “due to high sensible heat and low air density”.

Response: It has been added. Line 67-68

Line 84-86, A reference is necessary for this result.

Response: We have added the reference. Line 87-89
In addition, we have also examined the AOD observation data from the two stations: Nam Co and QOMS and found that it is true.

Line 103, “in the TP”

Response: It has been revised. Line 107

Line 142, “pristine continental environment”?

Response: The “pristine continental” has been revised to “pristine continent”. Line 146

Line 145, “be regarded a a …” should be “be regarded as a …”

Response: It has been revised. Line 149

Line 205-207, It might be better to indicate the unit too.

Response: We indicated the unit and the corresponding changes in order of magnitude in Equation (1). Line 209-214

Line 209-211, Actually, some other types of aerosols could also serve as INP, thus I would suggest adding “in model” here to constrain.

Response: It has been added. Line 218-219

Line 231-276, What is the spin-up time for the simulations?

Response: As the precipitation mainly occurred between 06:00 and 11:00 and there was no precipitation in the first few hours, it can be seen as a spin-up time in the first few hours (i.e., 00:00-05:00 UTC, 24 July, 2014). Line 257-288

Line 304-306, Considering the potential uncertainties, one digit number might be enough for the increase.

Response: We agree. However, we just want to make the point that the ice phase water condensate increased from clean to polluted simulation (Fig. 5). Considering that we have mentioned that point in the analysis in Fig. 7, we deleted Fig. 5 and corresponding text to make the article more focused.

Line 322, "occurs" should be "is"

Response: It has been revised. Line 315

Line 351, This is not accurate. Early description said 2 times concentrations, while here shows "2 times more abundant than …"

Response: We have revised it as "2 times". Line 342

Line 365-366, Particularly over the Pearl River Delta region as a few studies indicated, which are worthy to cite. Note that this should be also related to aerosol types.

Response:

Sun and Zhao (2021) investigated the influence of aerosol on the start and peak times of precipitation over three regions with different aerosol types, which are North China Plain (NCP), the Yangtze River Delta (YRD), and the Pearl River Delta (PRD). The results indicate that absorbing aerosols near surface can advance the precipitation formation time and peak time via radiative absorbing effect, while scattering aerosols near surface can delay the precipitation formation time and peak time via cooling effect. We think it would be better to mention it in the introduction part to make the introduction more comprehensive. Line 50
Also A few more studies have been cited here. Line 355-358

Anonymous referee #2: RC3

This study investigated the possible aerosol impacts on the small-scale convection and related precipitation event in Tibetan Plateau (TP) by conducting modeling sensitivity simulations. The analysis on cloud response to aerosol perturbations are generally sound in this study and the evidences shown to support their conclusions are overall sufficient. Given that there are still limited studies on aerosol-cloud-precipitation interactions over pristine continental regions like TP, I recommend it for publication but with some further clarifications of aerosol initial condition settings (or assumptions) prior to publication.

Thank you very much for your constructive comments and suggestions. Our point-by-point replies are given as below, and the corresponding revisions are made in the previous manuscript. **Line number below refers to the clean version**, while changes are tracked in the tracked version.

General comments:

1. Lines 134-135: Could the authors elaborate a little more about the motivations on studying the small-scale convection and precipitation event which occurred in Naqu region? Was there any unique characteristics of the precipitation event selected for study? For example, was there aerosol intrusion during the precipitation event? How frequent and how important of the small-scale convections related precipitation in TP region?

Response:
First, the small-scale convection and precipitation occurs with high frequency over the Tibetan Plateau (Gao et al., 2016). Satellite observation showed that convective clouds accounted for more than 80% of the total cloud cover in summer, which was comparable to that in the tropical oceans (Ye, 1981). Using 3-year Tropical Rainfall Measuring Mission precipitation radar (TRMM/PR) data, Fu et al. (2006) revealed that most isolated convective cells dominated in the central TP region, and more than 65% of the precipitation rate was less than 0.5 mmh^{-1}.

Second, Naqu has a relatively flat plateau with a simple meadow surface (Cheng et al., 2022). The influence of the terrain in Naqu is small. In addition, due to the sparse distribution of observations over the TP region, Naqu weather station collected sounding, rain gauge, and the Ka-band cloud radar in summer, 2014. These factors motivate us to study the small-scale convection and precipitation event which occurred in Naqu region in summer, 2014.

We changed the sentence in the text as "The typical convective precipitation event in Naqu, a city in the relatively flat plateau with a simple meadow surface, on 24 July 2014 is selected for simulation." Line 230-231

2. Below I have some concerns about aerosol condition setups when conducting simulations:

Lines 267-271: How better the aerosol field adopted in the TP case can represent the real situation? And how was the aerosol vertical distribution set, which is also believed of importance in determining the CCNs involved in cloud development? It's better to use available observations to validate the aerosol setups used in this study. One option the authors might consider is to use satellite retrieved AOD as reference.

Response:

The default setting in control simulation is not from auxiliary aerosol climatology, and it is described as "When the namelist variable, 'use_aero_icbc' is set to false, the Thompson and Eidhammer (2014) scheme will assume all model horizontal grid points have the same vertical profiles of water nucleating aerosols (CCN, also known as number of water-friendly aerosols, NWFA) and ice nucleating aerosols (IN, also known as number of ice-friendly aerosols, NIFA). These profiles are controlled by parameter settings of variables at the top of 'phys/module_mp_thompson.F': naCCN0 (300 per cubic centimeter) is the near-surface value of CCN and naCCN1 (50 per cubic centimeter) is the free tropospheric value of CCN." (https://www2.mmm.ucar.edu/wrf/users/physics/mp28_updated.html).

Aerosol field adopted in the TP uses the MERRA-2 aerosols on 23 July 2014. The input MERRA-2 inst3_3d_aer_Nv data contains the following variables: mass mixing ratios of sea salt (SS, five bins), sulfate (SO_4), organic carbon (OC), black carbon (BC), and dust (DU, five bins). The characteristic particle sizes, density parameters, and particle size ranges were obtained with reference to the aerosol radius distribution file of MERRA-2 (Chin et al., 2002). The aerosol number concentrations are calculated at the WRF pre-processing stage by assuming a log-normal distribution with characteristic diameter and geometric standard deviation in the concentration (Thompson and Eidhammer, 2014). The vertical distribution of the aerosol number concentration is based on the mixing ratio of these species in each model layer. The vertical distribution of aerosol number concentration is shown in Fig. S1.

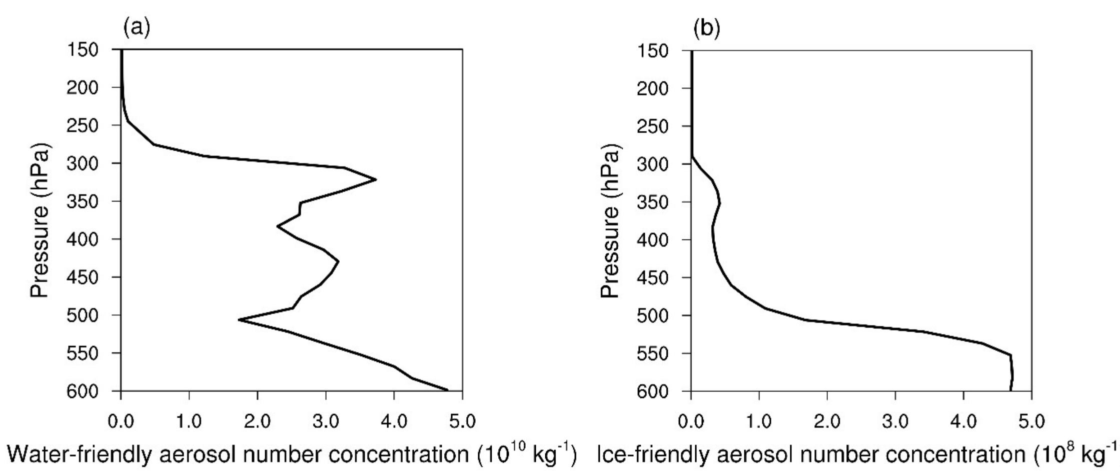

Figure S1. Vertical distribution of aerosol number concentration at 00:00 on 24 July 2014 in the 1°x 1° area around Naqu (31-32° N, 91.5-92.5° E, area B).

As observational aerosol data are sparse over the TP (at least near Naqu), and uncertainties are incurred when satellite retrievals are used over the TP, due to the complicated reflection of the land surface (Yang et al., 2020; Zhao et al., 2020; Jiang et al., 2022), we use the Modern-Era Retrospective analysis for Research and Applications Version 2 (MERRA-2) reanalysis to derive the cloud condensation nuclei number concentration. MERRA-2 aerosol reanalysis assimilates space-based observations of aerosols (Randles et al., 2017), and the Cloud-filtered Aerosol Robotic Network (AERONET) AOD data are used as input in a neural network to integrate Moderate Resolution Imaging Spectroradiometer (MODIS) radiances into the bias-corrected AOD. Therefore, it can be regarded as the real-time background to some extent. Comparing these two settings, we think the aerosol field adopted in the TP case can represent the real situation better.

Regarding the aerosol perturbation scenarios, Table 4 describes that the Clean case was set with 1/10 CCN number concentration at the basis of Control case, but from Fig. 4 it shows they are comparable in aerosol number concentration. So, could you explain the inconsistency between Fig. 4 and Table 4?

Response:

It is consistent. Please note the color bars, which indicate the difference.

IN may also play a role in aerosol-cloud-precipitation. Are there any perturbations in IN loadings among different experiments?

Response:

Yes, IN also has perturbations among different experiments. In Fig. 8 (Fig. 7 in new manuscript), the role of IN plays a role in the layer above 300hPa, where simulated cloud ice and snow increase with IN loading. The freezing effect of IN also invigorates the convection. However, the number concentration of IN is orders of magnitude smaller than that of CCN. Therefore, we emphasis on the analysis the role of CCN, which dominates in the convection.

We indicate it in Table 4 to clarify. Line 287-288

3. Is there any influence on surface precipitation types due to either CCN or IN effects? That is, what are the relative contributions by rain and snow to surface precipitation and/or their temporal/spatial variations?

Response:

During this precipitation simulation, surface precipitation types are mainly rain and a small amount of graupel. The temporal variation of the contribution by graupel to surface precipitation is shown in Fig. S2. The biggest rate of graupel to surface precipitation are 6.913%, 7.833%, 14.004%, and 26.376% for clean, control, TP, and polluted, respectively. It shows that as pollution increases, the rate of graupel to surface precipitation increases, which indicates that the transformation of cloud water to graupel and the development of convective clouds are favored as pollution increases.

We have added a sentence in the relevant text “The proportion of surface graupel to the total precipitation increases from 6.913%, 7.833%, 14.004%, and 26.376% in clean, control, TP, and polluted, respectively.” Line 381-383

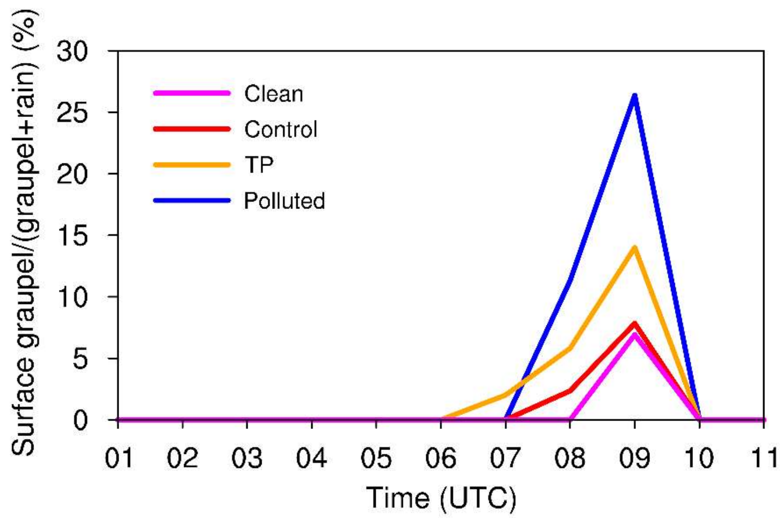

Figure S2. Time series of the contribution by graupel to surface precipitation in area A (31.4-31.5°N, 92.0-92.1°E) from 00:00 to 11:00 UTC on 24 July 2014.

Minor comments:

Line 50: ‘Due’ -> ‘Due to’.

Response:

It has been revised. Line 51

Fig. 3: What are A and B for? Please denote it in the caption.

Response:

We have added one sentence in the text before Fig.3 to clarify. Line 264-267
“The precipitation in the 0.1°x 0.1° area around Naqu (31.4-31.5° N, 92.0-92.1° E, area A) and the distribution of the aerosol number concentration in the 1°x 1° area around Naqu (31-32° N, 91.5-92.5° E, area B) is are examined in our detailed analysis.”

Fig. 4: Please use the same color bar to better view the difference between the four cases.

Response:

We tried the same color bar and we think it is better to present as the new Fig.4.

Fig. 6: What are the possible reasons the TP case overestimated the precipitation amount observed?

Response:

We think the possible reason may partly due to the inaccurate observation data. The observation data here is the gauge-satellite merged hourly precipitation product with a grid spacing of 0.1° × 0.1° (Shen et al., 2014). Note that in Fig. 1 that the automatic rain gauge observed 24-hour accumulated precipitation amount at Naqu station was 5.8 mm, but only light rainfall (0.1~1 mm) appeared at Naqu and its surrounding areas in the gauge-satellite merged precipitation product. The inconsistence between the precipitation observation data is due to the coarse resolution and retrieval error over TP. However, they are the best data we could obtain. That's why we emphasis on the analysis of the microphysical process in different model simulations and call for the more sustained and comprehensive observations over the Tibetan Plateau. It is the prerequisite for better understanding the aerosol impact on precipitation formation in this region.

Fig. 9: How about put all the Z-wind profiles in one panel so that the readers can more easily view the differences among different cases?

Response:

Fig.9 (Fig.8 in the revised manuscript) has been updated to put all the Z-wind profiles in one panel.

Anonymous referee #3: RC2

The authors have used model simulations driven by reanalysis to examine aerosol effects on convection over the Tibetan Plateau, an area with very low concentrations of aerosols normally. Their findings are consistent with other works, showing that generally with increased aerosols they see delayed warm rain production and then enhanced cold rain processes with some convective invigoration. I see no major flaws with the work, I just have some suggestions below for clarification and better readability.

Thank you very much for your constructive comments and suggestions. Our point-by-point replies are given as below, and the corresponding revisions are made in the previous manuscript. **Line number below refers to the clean version**, while changes are tracked in the tracked version.

Overall:

Throughout there are some typos and small language/grammatical issues that require some copy-editing. I would suggest adding subtitles to figures, it's easier to follow that way.

Response:

The subtitles has been added in Fig.4, Fig.6, and Fig.7.

Specific:

Abstract is a bit confusing, what does this sentence mean?
"With the increase in the aerosol number concentration, the conversion of cloud water to rain in clouds is first enhanced." First according to what?

Response:

The sentence "With the increase in the aerosol number concentration, the conversion of cloud water to rain in clouds is first enhanced." refers to the TP simulation, which is slightly polluted. The "first" are compared with the polluted simulation "Under polluted situations, the conversion process of cloud water to rain is suppressed; however, the transformation of cloud water to graupel and the development of convective clouds are favored."

We changed it to "With the increase in the aerosol number concentration, the conversion of cloud water to rain in clouds is enhanced at first". Line 31-33

Line 127: The sentence starting with 'The aerosol impact in..' was confusing to read. I think you are just trying to state that impacts on convection can then effect teleconnections through the heat pump? Also, the reference is the 2007 paper, not 2016.

Response:

We try to state the role of aerosols in the teleconnections between the heat pump and the stronger convection and precipitation in the TP or downstream regions. The heat-hump study (Wu et al., 2007) mentioned the thermal forcing, while the reference Wu et al (2016) focused on the interactions between aerosols and monsoon in China.

We revised this sentence as "The role of aerosols in the teleconnections between the heat-pump and the stronger convection and precipitation in the TP or downstream regions (Wu et al., 2016) also needs to be accounted for in the weather forecasting models (Liu et al., 2019; Zhao et al., 2020)." Line 131-134

Line 146: 'This methodology could then be applied in other regions of the world with similar background environments.' I'm not sure which methodology you mean - just using model simulations driven by reanalysis? I'm certain this has been done numerous times in various regions of the globe.

Response:

This methodology here refers to the method that generate the aerosol background field for the WRF simulation according to the real-time aerosol reanalysis method as described in the paper, especially before year 2015 or in regions where aerosol observations are sparse. It can be regarded as a compromise method between WRF (without aerosol) and WRF-Chem (with more detailed chemistry process).

Line 236: Do you not have observations of convection and/or precipitation? Why do you need to compare the soundings to 'suggest' that convection developed in this time period?

Response:

We have the Ka-band cloud radar data and precipitation observation. A more detailed comparison of this precipitation process using the analysis of the vertically pointing Ka-band cloud radar observation is presented in Fig.4 in Cheng et al (2022), and we cited in Line 330-333. Considering the inconsistency of two precipitation dataset in Naqu, the sounding data here are used to better illustrate that the convection developed during 00:00 UTC to 12:00 UTC on 24 July 2014, in addition to radar and precipitation data.

Line 253: 1km and 60s are a bit coarse. (especially the 60s, was that truly used for the 1km grid?)

Response:

We did not express clearly that the time step for the outer layer is 60s, and for the inner layer is 2.4s. Normally, the time step is recommended to be set as 6*1000/1000, which is 6s. A triple nesting grid with spacing of 25 km, 5 km and 1 km are applied. Considering the observation data are relatively spare in the TP, we think 1km simulation is enough for the analysis in this study.

We have revised the sentence to clarify it. “an integration step of 60 seconds for the outer layer is applied” Line 264

Is there a reason this particular date/case was chosen?

Response:
First, the small-scale convection and precipitation occurs with high frequency over the Tibetan Plateau (Gao et al., 2016). Satellite observation showed that convective clouds accounted for more than 80% of the total cloud cover in summer, which was comparable to that in the tropical oceans (Ye, 1981). Using 3-year Tropical Rainfall Measuring Mission precipitation radar (TRMM/PR) data, Fu et al. (2006) revealed that most isolated convective cells dominated in the central TP region, and more than 65% of the precipitation rate was less than 0.5 mmh^{-1}.

Second, Naqu has a relatively flat plateau with a simple meadow surface (Cheng et al., 2022). The influence of the terrain in Naqu is small. In addition, due to the sparse distribution of observations over the TP region, Naqu weather station collected sounding, rain gauge, and the Ka-band cloud radar in summer, 2014. These factors motivate us to study the small-scale convection and precipitation event which occurred in Naqu region.

We changed the sentence in the text as “The typical convective precipitation event in Naqu, a city in the relatively flat plateau with a simple meadow surface, on 24 July 2014 is selected for simulation.” Line 230-231

What is the default value from the model and where does it come from? Why not perturb the observed aerosol value instead?

Response:

The default value is described on the WRF website page (https://www2.mmm.ucar.edu/wrf/users/physics/mp28_updated.html) as “When the namelist variable, 'use_aero_icbc' is set to false, the Thompson and Eidhammer (2014) scheme will assume all model horizontal grid points have the same vertical profiles of water nucleating aerosols (CCN, also known as number of water-friendly aerosols, NWFA) and ice nucleating aerosols (IN, also known as number of ice-friendly aerosols, NIFA). These profiles are controlled by parameter settings of variables at the top of 'phys/module_mp_thompson.F': naCCN0 (300 per cubic centimeter) is the near-surface value of CCN and naCCN1 (50 per cubic centimeter) is the free tropospheric value of CCN.”

As observational aerosol data are sparse over the TP (at least near Naqu), and uncertainties are incurred when satellite retrievals are used over the TP, due to the complicated reflection of the land surface (Yang et al., 2020; Zhao et al., 2020; Jiang et al., 2022), we use the Modern-Era Retrospective analysis for Research and Applications Version 2 (MERRA-2) reanalysis to derive the cloud condensation nuclei. MERRA-2 aerosol reanalysis assimilates space-based observations of aerosols (Randles et al., 2017), and the Cloud-filtered Aerosol Robotic Network (AERONET) AOD data are used as input in a neural network to integrate Moderate Resolution Imaging Spectroradiometer (MODIS) radiances into the bias-corrected AOD. Therefore, it can be regarded as the real-time background to some extent.

Line 299: You mention radar here, but why is this not shown anywhere? How do the simulated storms compared to what was observed?

Response:

The radar observation indicates that some scattered clouds existed at the height of 5–7 km before 0500 UTC. Convective cloud began to form after 0500 UTC with the cloud top height of ~9 km and disappear before 0900 UTC, which has similar pattern with our Control simulation analysis in Fig. 7b (Fig. 6b in new manuscript). Because a more detailed comparison of this precipitation process using the analysis of the vertically pointing Ka-band cloud radar observation is presented in Fig.4 in Cheng et al. (2022), and we cited. Line 330-333

Please note we have also deleted Fig.5 and corresponding text. In previous Fig. 5, we just want to say that, the ice phase water condensate increased from clean to polluted simulation. Considering that we have mentioned the point in the analysis in Fig. 7, we deleted Fig. 5 and the corresponding texts to make the article more concise.

Fig 5: I'm not sure how to interpret a cloud field that's averaged over 12 hours. Physically this doesn't make a lot of sense, as over this period of time advection, microphysics, and precipitation are all occurring.

Response:

The sounding data are twice per day at 00:00 and 12:00 UTC. In previous Fig. 5, we just want to say that, the ice phase water condensate increased from clean to polluted simulation. Considering that we have mentioned the point in the analysis in Fig. 7, we deleted Fig. 5 and the corresponding text to make the article more concise.

Line 302: You say 'indicating that the warm cloud process was dominant', but these are model simulations, and you should be able to easily check to see what processes are dominant.

Response:

It is mixed phase precipitation. However, that’s not our point which may confuse the reader. We have deleted Fig.5 and corresponding text.

Line 340: You are repeating yourself from the previous paragraph when you describe the figure here.

Response:

Fig. 7 (Fig.6 in the revised manuscript) has been redrawn to combine the 8 subplots to 4 subplots, and corresponding description also has been changed. Line 334-336

Line 356: I'm not sure I follow this argument. Might it just be the case that the extremely pristine environment is aerosol-limited?

Response:

Line 345-348: The reference here is used to explain that the precipitation intensity increases and the precipitation starts earlier with the increase of aerosol loading when the atmosphere is not heavily polluted. It is aerosol-limited environment. In Efraim et al. (2022), the activation of particles into cloud droplets high above the cloud base releases additional latent heat, increases the buoyancy, and invigorates the clouds also in consistence with the results here, especially explains the invigoration after rain out (Fig. 6c in new manuscript).

We combined these two explanations and changed this sentence to "This may be explained by aerosol-limited environment and the higher coalescence efficiency due to the secondary droplet activation in convective clouds, especially in relatively clean areas (Efraim et al., 2022)."

Figure 9: It might be easier to see differences if this was just one plot.

Response:

Fig.9 (Fig.8 in new manuscript) has been updated to put all the Z-wind profiles in one panel.

Line 401: These w averages are over a large domain, over 5 hours. There are different cloud/storm amounts in each simulation. It's not clear that you can interpret anything real from this plot, it would just be averaging over anything interesting. I would suggest looking only at updrafts, or use a condensate threshold, to be more sure this is actual invigoration.

Response:

We take the suggestion and look only the updrafts in clouds. The Fig. 9 (Fig.8 in new manuscript) has been updated.

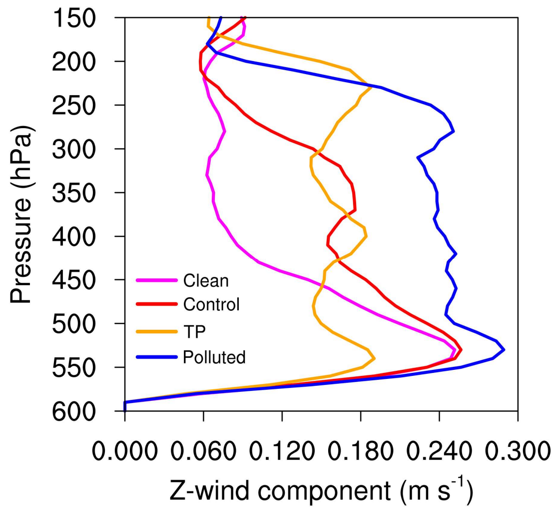

Figure 8. Updrafts in clouds in aera A (31.4-31.5°N,92.0-92.1°E) averaged from 06:00 to 11:00 UTC on 24 July 2014, in unit of m s^{-1}.

The conclusion feels kind of sudden and a bit non sequitur. There is talk of uncertainties in measurement, but not really in context of the study. It just seems kind of incomplete.

Response:

The study here relies heavily on model simulations, and the outcome should therefore be regarded as partial attempt to investigate a possible relationship between aerosol and convective precipitation in TP region. The difficulties we face during this study make us think it worthy to mention the uncertainties in measurement in conclusion and call for more sustained and comprehensive observations over the Tibetan Plateau. Because these are a prerequisite for better understanding the aerosol impact on precipitation formation in this region. We have revised the conclusion a little bit to improve the readability.