Answers to anonymous referee #2

We would like to thank the reviewer for his/her time and effort reviewing our study. We have found the comments to be constructive and helpful.

In this reply, the comments from the reviewer are in black, and our answers are in red. The new text and lines of the revised document where the adjusted text can be found are also in red. In the revised document, all new text is marked in blue, and deleted text is crossed out in red.

Major comments:

1. introduction section is a bit confusing for me. A lot of studies and findings were simply listed in a detailed but unclear way. In the end, it is still not clear what are the challenges in this topic and especially why this study is novel, which hampers the manuscript. I recommend the authors to revise this section into a good story.
   A: We agree with the reviewer and have revised the introduction section.

   An explanation of the opposite effect of aerosols on convection has been added.

- "Observational and model simulation studies have shown different results for aerosol effects on deep convection, suggesting that aerosols may either invigorate or inhibit precipitation, depending on the type and concentration of aerosols and environmental conditions (Jiang et al., 2018; Khain 2009; Fan et al., 2009, 2013; Rosenfeld et al., 2008, 2014)."

- Lines 84-99 of the original manuscript are simply a list of relevant studies, which are not very closely related to the present work and have been deleted.

  An elaboration has been added about the main challenges facing the study of aerosol-cloud-precipitation interactions and how scientists are trying to solve the problem.

- "A great challenge in observational study on the indirect effects of aerosols is to distinguish the isolated contributions of weather conditions (dynamic conditions) and aerosol microphysical effects to the observed macro-micro features of clouds and precipitation (Stevens and Feingold 2009; Tao et al., 2012; Rosenfeld et a1., 2014; Li et al., 2017). This is especially true for mesoscale convective systems (MCSs) that are heavily affected by large-scale atmospheric circulation. Some studies have adopted this ideals to constrain the variations of dynamical factors, cloud type, stages of cloud precipitation development and etc., and then to analyze the influence of aerosols (Rosenfeld et al.,2008; Fan et al.,2013, 2018; Li et al., 2011b; Min et al.,2009; Li and Min,2010; Gibbons et al., 2018). For example, Fan et al. (2013) found that the thermodynamic effect of aerosols (freezing of cloud water to release additional LH) contributes up to 27 % to the increase in cloud cover during the growth stage of deep convective clouds in summer, while the microphysical effect of aerosols (freezing of large amounts of cloud droplets to produce more and smaller ice particles) increases cloud cover and cloud top height during the mature and dissipation stages."

We have also added explanations why this study is novel.

- "And we attempt to isolate the impacts from meteorology conditions and aerosol conditions on the vertical structure of precipitation and LH by analyzing multiple satellite observation with new mathematic treatment."

2. section 3.2 is important and actually contains quite a lot interesting findings. But only the simple descriptions were presented without giving any discussion, implication or even comparison with previous studies. After reading this section, I don't really get scientifically useful information. It's more like a technical report.
   A: Yes, we have added more discussions, comparisons with results in other studies, and some hypotheses into this section. The revised statements are as shown here:
   - "Although followed by a layer with slower growing, the final NSRR for given PTT under dusty condition (solid curve) still is heavier than that of pristine rains (dotted curve). Such effect is weak for stratiform rains particularly those with relatively warm PTTs (e.g. light blue and green curves in Fig. 4d). This is because the proposed dust's IN effect generally works for ice-phase microphysical process. For those stratiform rains start from warm PTTs, there is no sufficient water content and the temperatures are too warm for the heterogeneous freezing to take place."

   - "This indicates a possible suppression by dusty conditions for warm rain growth. During the long-range transportation of dust from north to southeastern China, very likely the dust particles were coated by soluble aerosols and become active CCN (Li et al., 2010) in the warm rains. For given condensed liquid water content, this additional CCN leads to smaller cloud effective radius thus decreases the coalescence efficiency which is the main mechanism for warm rain growth (Rosenfeld et al., 2008; Min et al., 2009; Yin and Chen, 2007; Li et al., 2010)."

   - "Validation of satellite retrieved LH is still a very challenging task (Tao et al., 2022) because there is no directly measured ground-truth of LH available. Intercomparison among different LH products is one of the useful indirect means to evaluate their accuracy. Based on Li et al., (2019a), VPH product showed reasonable structure of LH in Tibetan Plateau with similarities and dissimilarities comparing to CSH and SLH. In this study, the VPH product was chosen because it is directly related to the variations of precipitation rate at each altitude, while CSH and SLH retrievals use constrains of precipitation rate at surface, precipitation top height, precipitation type, etc. It should be emphasized, the LH-related results did not receive rigorous validation in this study area, thus should be treated with cautions."

Specific comments:

1. Line 16: How did author define the 'pristine days'? It is incorrectly used if the authors only meant days with low dust concentrations, because other aerosol can dominate especially over east China.

   A: We clarified this point in the revision:

   "If the mean total AOD is less than 0.2, the day was defined as pristine day."

2. In lines 49-57, the author showed the findings of dust aerosol weakening convection precipitation but immediately in lines 59-65 the opposite was listed. I would expect at least an explanation / mention here.

   Line 65: Yes, we added associated explanations in the revision as:

   "Observational and model simulation studies have shown different results for aerosol effects on deep convection, suggesting that aerosols may either invigorate or inhibit precipitation, depending on the type and concentration of aerosols and environmental conditions (Jiang et al., 2018; Khain 2009; Fan et al., 2009, 2013; Rosenfeld et al., 2008, 2014)."

3. Lines 133-136: this is a repetition of lines 130-132.

   A: Thanks for reminding us, and lines 130-132 have been deleted.

4. MODIS-retrieved aerosol size parameters have little quantitative skill over land (e.g., https://doi.org/10.5194/amt-4- 201-2011). Thus, derivation of CMAOD from FMF is not a good try.

   A: Yes, we agree. We clarified this point in the discussion part with three comments. Firstly, there has been a lot of literature using CMAOD to represent the AOD of dust. Secondly, we verified that the CMAOD of MODIS is dust using CALIPSO's aerosol and cloud vertical and horizontal distribution products (vertical feature mask product). Finally, we performed sensitivity tests to randomize the CMAOD to produce errors within ±20%, and the results showed that changes in the CMAOD do not have a subversive effect on our conclusions.

   We clarified this point in the discussion part in the revision as:

   - "There are uncertainties in the MODIS retrieval of aerosols over land (Chu et al., 2002), and the uncertainty in the FMF retrieval is about ±0.2 (Tanre et al., 1996; Tanre et al., 1997). There is still a lack of long-term, large-scale dust observation product to solve this problem precisely. Instead, multiple studies were conducted based on MODIS retrieved FMF information. For example, Kaufman et al. (2002, 2005) and Gao et al. (2001) have utilized the FMF-derived CMAOD as representation of dust to study the transport and deposition of dust and its impact on the climate system. Min et al. (2009) and Li et al.

(2010) applied MODIS derived coarse mode AOD to classify dust aerosols over Atlantic Ocean to study their impacts on cloud and precipitation profiles.”

- “The Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) Level 2 lidar vertical feature mask (VFM) data product uses the particle depolarization ratio to determine the dust. However, CALIPSO only has nadir observations, and the data obtained from narrow orbits are very limited. Therefore, we did not use the CALIPSO data as the basis for judging dust in this study. However, it can be used as a supporting evidence for the adoption of CMAOD by MODIS to determine dust. For example, CMAOD shows a typical dusty precipitation day on June 25, 2011 and July 9, 2011, and CALIPSO's VFM product likewise shows that the aerosols on that day were indeed predominantly dust (Fig. S7).”

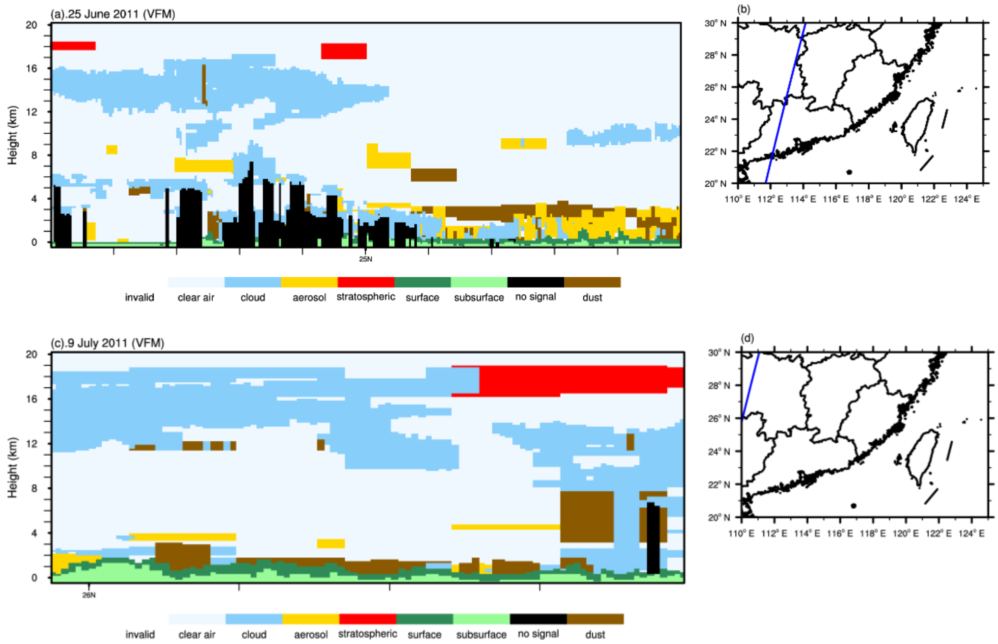

Figure S7: On June 25, 2011 and July 9, 2011, the vertical and horizontal distribution of cloud and aerosol layers observed by the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) lidar vertical feature mask (VFM) data product. Where the blue line in indicates the CALIPSO footprint.

- “We performed a sensitivity test assuming that there is a random error of up to ±20% in CMAOD and that the PTT-NSRR relationship for the new data (Fig. S8) and the original data (Fig. 10) remain unchanged. That is, there is some error in CMAOD, but it does not subvert the conclusions of this study.”

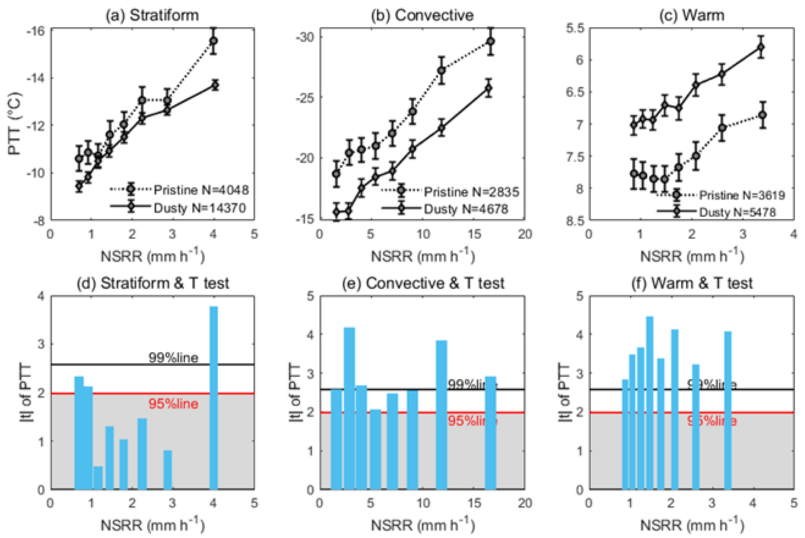

Figure S8: The precipitation top temperature (PTT) against near surface rain rate (NSRR) for new stratiform (a) , convective (b) and warm (c) precipitation samples under pristine (dotted curves) and dusty (solid curves) conditions (the first row). For a given NSRR, t test significance for differences in PTT between stratiform (d), convective (e) and warm (f) precipitation in pristine and dusty conditions (the second row), red (black) line indicates the 95 % (99 %) confidence level at 100 degrees of freedom.

5. In addition, how did the author consider the aerosol humidification effect in the presence of precipitation.

   A: Yes, we agree with the reviewer. And we admitted that aerosol humidification effect is important. In this study, the effect may increase the retrieving error of FMF in MODIS aerosol product, however, we have not considered such effect. Firstly, the MODIS algorithm filters out pixels within 1 km of detectable clouds, where the effect of aerosol humidification will be the greatest (Martins et al., 2002). And this algorithm significantly reduces the effect of relative humidity on aerosol optical depth retrievals (Remer et al., 2005). Secondly, the relationship between aerosol hygroscopic growth and the surrounding relative humidity values can be described by a single parameter representation, namely the kappa parameterization (Petters and Kreidenweis, 2007):

$$\mathrm{g}(\kappa, \mathrm{RH}) = \left(1 + \kappa \cdot \frac{RH}{100-RH}\right)^{1/3},$$

   where g is the hygroscopic growth factor, κ is the aerosol hygroscopicity (atmospheric particulate matter is typically characterized by $0.1<\kappa<0.9$) and RH is the relative humidity value (%). Altaratz et al. (2013) performed radiative transfer calculations using 12 years of June-August radiosonde measurements and found that at continental stations, the AOD increased by 4% and 5% for the 1 km and 2 km layers, for $k = 0.3$, respectively, and by 5% and 4% for $k = 0.7$. That is, the effect of changes in relative humidity on AOD is limited. In this study, we have not considered the hygroscopic growth of aerosols. Assuming a 5% hygroscopic growth of AOD, the relative increase of $\frac{\partial PTT_0}{\partial AOD}$ for stratiform (convective) precipitation is 2.8% (3.3%). Such effect will not significantly change our conclusion.

And, we added a discussion of aerosol humidification effects in the revision as:

"In this study, we have not considered the aerosol humidification effect in the presence of precipitation, which may increase the retrieving error of FMF in MODIS aerosol product. Firstly, the MODIS algorithm filters out pixels within 1 km of detectable clouds, where the effect of aerosol humidification will be the greatest (Martins et al., 2002). And this algorithm significantly reduces the effect of relative humidity on aerosol optical depth retrievals (Remer et al., 2005). Secondly, Altaratz et al. (2013) performed radiative transfer calculations using 12 years of June-August radiosonde measurements and found that at continental stations, the AOD increased by 4% and 5% for the 1 km and 2 km layers, for aerosol hygroscopicity = 0.3, respectively, and by 5% and 4% for aerosol hygroscopicity = 0.7. That is, the effect of changes in relative humidity on AOD is limited. In our study, assuming a 5% hygroscopic growth of AOD, the relative increase of $\frac{\partial PTT_0}{\partial AOD}$ for stratiform (convective) precipitation is 2.8% (3.3%). Such effect will not significantly change our conclusion."

6. Lines 167-169: But it's not always the case and even rarely happens that one precipitating grid can be surrounded by eight clear-sky grids.
   A: We completely agree with the reviewer that one precipitating grid can be not always surrounded by eight clear-sky grids. Actually, such grids were excluded from this study out of this concern.

   We clarified this point in the revision as:
   "Because AOD is not available under cloudy sky, for each 1×1 grid where precipitation was detected by TRMM PR, the averaged AOD and CMAOD from the surrounding eight grids are assigned to this grid. If the AOD of all eight grids are missing, then the precipitating grids AOD were recorded as missing, and such grids were excluded from this study. Otherwise the averaged AOD from the 8 grids AOD is assigned to precipitating grid (it is not required that all 8 grids have AOD observations)."

7. Lines 169-171: Did the author take the study region as a whole when defining "dusty day"? For example, for a individual day, mean clear-sky CMAOD

surrounding precipitating grids is larger than 0.5, in this case, how did the authors deal with other clear-sky CMAOD far away from precipitation? Also classify it as dusty days? This is not clear.

A: We took the study region as a whole when defining “dusty day”, and the mean CMAOD from all precipitating grids at the same day were calculated. If the mean CMAOD is larger than 0.5, then the day was defined as “dusty day”. And all rain samples in that day were defined as polluted rains or dusty rains. If the mean total AOD is less than 0.2, the day was defined as pristine day, and all rain samples in that day were defined as pristine rains.

It is possible that some rainy samples in dusty days have relatively low AODs because they were far from the dust plume, and vice versa. It was found that, under this classification criteria, for convective (stratiform) precipitation, over 83% (84%) precipitating grids in pristine days showed total AOD lower than 0.2, and over 87% (79%) precipitating grids in dusty days showed CMAOD heavier than 0.5. In another word, such method can represent the main feature of aerosol condition and it has the advantage to show the large-scale atmospheric circulation as an “ensemble” comparing to the method of defining the aerosol condition for each precipitation grid separately.

We clarified this point in the revision as:

“If the mean CMAOD is larger than 0.5, then the day was defined as “dusty day”. And all rain samples in that day were defined as polluted rains. If the mean total AOD is less than 0.2, the day was defined as pristine day, and all rain samples in that day was defined as pristine rains. Under this classification criteria, for convective (stratiform) precipitation, over 83% (84%) precipitating grids in pristine days showed total AOD lower than 0.2, and over 87% (79%) precipitating grids in dusty days showed CMAOD heavier than 0.5. In another word, such method can represent the main feature of aerosol condition and it has the advantage to show the large-scale atmospheric circulation as an “ensemble” comparing to the method of defining the aerosol condition for each precipitation grid separately.”

8. Line 173: It’s better to clarify how the authors did the spatial and temporal co-locations between TRMM and ERA5?

   A: We clarified this point in the revision as:

   “For each TRMM PR detected raining pixel, the daily averaged ERA5 variables averaged from all grids ±0.5° surrounded it are assigned to it.”

9. Lines 227-229: It is true for convective clouds but not for stratiform clouds. Can the authors explain the reason?

   A: Thanks for pointing this out. The impacts of dust aerosol on stratiform rain at low layers close to surface is weaker than that on convective rains, particularly for those stratiform rains with warmer PTTs (e.g. light blue and green curves in Fig.4d). This is because the proposed dust’s IN effect generally works for ice-phase microphysical process. For those stratiform rains starting from warm PTT, there is no sufficient water content and the temperature may be too warm for heterogeneous freezing to take place.

In the revision, we modified the statement as:
"Although followed by a layer with slower growing, the final NSRR for given PTT under dusty condition (solid curve) still is heavier than that of pristine rains (dotted curve). Such effect is weak for stratiform rains particularly those with relatively warm PTTs (e.g. light blue and green curves in Fig. 4d). This is because the proposed dust's IN effect generally works for ice-phase microphysical process. For those stratiform rains starting from warm PTTs, there is no sufficient water content and the temperatures are too warm for heterogeneous freezing to take place."

10. Line 231: Please develop a bit how dust can suppress warm rain?
A: Thanks, and we have added an explanation about this in the revision as:

"This indicates a possible suppression by dusty condition for warm rain growth. During the long-range transportation of dust from north to southeastern China, very likely the dust particles were coated by soluble aerosols and become active CCN (Li et al., 2010) in the warm rains. For given condensed liquid water content, this additional CCN leads to smaller cloud effective radius thus decreases the coalescence efficiency which is the main mechanism for warm rain growth (Rosenfeld et al., 2008; Min et al., 2009; Yin and Chen, 2007; Li et al., 2010(Li et al., 2010)."

11. Lines 236-239: As I understand, the contoured frequency by altitude diagrams is 2D probability density distribution, which represents how the data concentrate. Thus, it can not be used to illustrate if dust increases or decreases LH for a specific altitude. To do so, one should normalize data so that probability sums to 1 for each altitude, so called 'joint-histgram' .
A: Thanks for the comments. The reviewer is right, and the joint PDF can be calculated as

$$\mathrm{JPDF(i,j)} = \frac{\mathrm{N(i,j)}}{\sum_{i=1}^{TN1} N(i, j=j)} \times 100\%$$

where N(i,j) is the number of samples with LH in the ith bin and altitude (H) in the jth bin. TN1 is the total number of classified bins of LH. The denominator here is the total number of samples summed at certain altitude in the jth bin.

In Figure 5, we calculated the probability using total samples in the Height-LH phase space as the unified denominator.

$$\mathrm{PDF(i,j)} = \frac{\mathrm{N(i,j)}}{\sum_{i=1}^{TN1}\sum_{j=1}^{TN2} N(i,j)} \times 100\%$$

TN2 is the total number of bins of altitude.

Therefore, for certain altitude, the PDF(i,j) is based on the same denominator and can be compared between dusty and pristine samples.

12. Figure 6: Three LH methods are quite different with each other. I was wondering if the LH profiles are reliable? Why did author chose VPH in Figure 5? I don't see any validation studies were cited. It is expected that the results will change quite a lot and also the conclusion will not hold anymore if other two methods are used since the vertical profiles have large difference as shown in Fig. 6.

A: Thanks for the comments. Validation of satellite retrieved LH is a very challenging task (Tao et al., 2022) because there is no directly measured ground-truth of LH available. Intercomparison among different LH products is one of the useful indirect means to evaluate their accuracy. Based on Li et al., (2019), VPH product showed reasonable structure of LH in Tibetan Plateau with similarities and dissimilarities comparing to CSH and SLH.

In this study, the VPH product was chosen because it is directly related to the variations of precipitation rate at each altitude, while CSH and SLH retrievals did not use this detailed information, instead, they use constrains of precipitation rate at surface, precipitation top height, precipitation type.

Although the mean vertical profiles of LH are different among VPH, CSH and SLH, agreements are met regarding the relative difference between pristine and dusty convective rains. As shown in Figure 6, all three products agree that LH in deep convective precipitation at middle layer (around 5-6 km) in dusty condition should be stronger than those in pristine condition. For stratiform rains, VPH shows a stronger latent heat in the dusty condition near 5-6 km. There also is a slight enhancement of LH in dusty samples based on SLH and CSH products (Figure 6a, red and green curves), although this is not remarkable.

Based on the above analysis, we decided to keep the LH-related results in the manuscript, but added a discussion regarding the uncertainties of satellite LH products as this:

"Validation of satellite retrieved LH is still a very challenging task (Tao et al., 2022) because there is no directly measured ground-truth of LH available. Intercomparison among different LH products is one of the useful indirect means to evaluate their accuracy. Based on Li et al., (2019a), VPH product showed reasonable structure of LH in Tibetan Plateau with similarities and dissimilarities comparing to CSH and SLH. In this study, the VPH product was chosen because it is directly related to the variations of precipitation rate at each altitude, while CSH and SLH retrievals use constrains of precipitation rate at surface, precipitation top height, precipitation type, etc. It should be emphasized, the LH-related results did not receive rigorous validation in this study area, thus should be treated with cautions."

13. Line 254: Why the warm rain was sometimes included and but sometimes not? Any reason?

A: In section 3.3 we defined the three-layer precipitation growth rate using the method mentioned in lines 150-158 to investigate the effect of dust aerosols on the growth rate of precipitation in each layer. Those slopes include SlopeA in the layer with temperatures colder than -5°C, SlopeB in the middle layer with temperatures between -5°C to 2°C, and SlopeC in the lowest layer with temperatures warmer than 2°C.

Because warm rain has precipitation top temperature warmer than 0 °C and there is almost no ice phase microphysical processes in it, SlopeA and SlopeB cannot be calculated from them. We have removed lines 254-255 from the text and added warm rain in the supporting information (Figs. S2 and S5).

And We added the discussion of Slope C in warm rain in the revision as:

"As for warm rain (Fig. S2), for a given NSRR, SlopeC increases with increasing PTT. For a given PTT, SlopeC increases with NSRR. Even when both PTT and NSRR are constrained, SlopeC in dusty conditions is still significantly weaker than that in pristine conditions (Fig. S2c)."

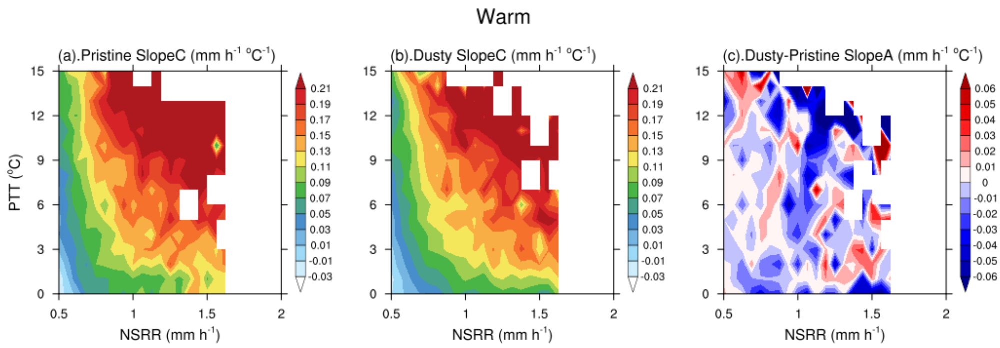

Figure S2: The mean SlopeC for warm rain as functions of near surface rain rate (NSRR) and precipitation top temperature (PTT) in pristine (the left column) conditions, dusty (the middle column) conditions and the differences between them(dusty minus pristine, the right column).

"As for warm rain, the SlopeC in dusty condition is significantly smaller than that in pristine condition and the t testing showed that differences of SlopeC exceeded the 99 % confidence level (Fig. S5), indicating that dust suppressed warm rain. In addition, polluted dust particles may also act as CCN to decrease the effective radius of cloud droplets and inhibit the coalescence efficiency (warm rain) as suggested by Rosenfeld (2008), Li et al. (2010), Min et al. (2009) and Yin and Chen (2007)."

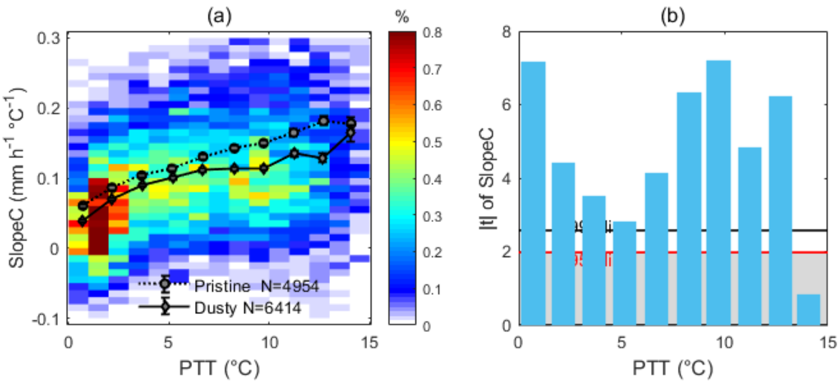

Figure S5: The mean Slope C as functions of precipitation top temperature (PTT) for warm rain under pristine (dotted line) and dusty (solid line) conditions (a). Overlapped are the contoured occur frequency (%) of samples under dusty conditions. For a given PTT, t test significance for the differences between SlopeC of warm rain for pristine and dusty conditions (b), red (black) line indicates the 95 % (99 %) confidence level at 100 degrees of freedom.

14. Figure 9: It's interesting that the dependence of Slope on PTT is getting stronger from C to A. Could the authors develop a bit on this? Also, Fig.9 was kind of repeating Fig.7 & 8. Although the plot types are different, all information as discussed in Fig 9 can be also seen in Fig 7&8. I recommend the author to condense a bit or put one into SI.

A: Thanks for the question.

Because the precipitation particle growth rate at upper layer (water vapor deposition process) and middle layer (aggregation and riming process) are critical to determine the final surface rain rate, SlopeA and SlopeB are more sensitive to PTT. As for SlopeC in the lower layer, the convective precipitation rate has a slight increase due to coalescence with cloud droplets. However, in the layer very close to surface, rain rate no longer grows but decreases due to breakup and/or evaporation. For the stratiform precipitation, rain rate in this layer does not grow due to the lack of updraft. Therefore, SlopeC is not sensitive to PTT.

We agree with the reviewer that Fig.9 is kind of repeating Fig.7 & 8, and we have moved Fig. 9 to the supporting information.

The above explanations were added into the revision as:

"It is interesting that the dependence of Slope on PTT is getting stronger from C to A (Fig. S3). The precipitation particle growth rate at upper layer (water vapor deposition process) and middle layer (aggregation and riming process) are critical to determine the final surface rain rate. SlopeA and SlopeB are more sensitive to PTT. As for SlopeC in the lower layer, the convective precipitation rate has a slight increase due to coalescence with cloud droplets. However, in the layer very close to surface, rain rate no longer grows but decreases due to breakup and/or evaporation. For the stratiform precipitation, rain rate in this layer does not grow due to the lack of updraft. Therefore, SlopeC is not sensitive to PTT."

15. Line 313-315: What is the regression slope mentioned here? Can the authors explain more? How can the similar slopes indicate the growth rates of rain drops are similar under 'pristine environment'?

    A: We clarified this point in the revision as:

    "Meanwhile, it was found the linear regression slopes of K in Eq. (1) are similar between different CAPEs (Fig.9 d-f). It indicates the final rain rate reaching earth surface NSRR is proportional to the PTT with the same coefficient of 1/K. In another words, the growth rates of rain drop along the falling path are similar under pristine environment."

16. Line 331: Good idea!

    A： Thanks for the encouragement!

17. Lines 322-323: Any references support such argument?

    A: We added the reference to the manuscript.

    "Previous investigations demonstrate that K is relatively stable for different CAPES or aerosol conditions (Dong et al., 2018; Li et al., 2011a), so we mainly focus on the variations of PTT_0."

References

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