Reply to the comments by Reviewer #1

We thank the reviewer for his/her comments and suggestions on improving our manuscript. These comments are incorporated into the manuscript now. Below is our point-by-point response to these comments. The reviewer's comments are in italic and our responses are in normal font.

The manuscript mainly studies what rainfall rates are most efficient for wet removal (scavenging amount mode) of different aerosol species in different sizes by using CAM5 with and without the stochastic convection cases. The authors found that larger particles are easier to be removed by lighter rainfall and further suggest the frequency of light precipitation plays a more important role in regulating the amount of aerosol wet scavenging than that of rainfall. Meantime, the authors also pointed out that convective precipitation has higher efficiency in removing aerosols than large-scale precipitation over the globe even though convection is infrequent over high-latitudes. In general, the study is important to understand the relation between rainfall and aerosol wet scavenging. In addition, the paper is well written and presented in a logical way. But, some interpretations and discussions are unclear or missed. I therefore recommend publication of this paper in ACP after major revision. My comments are listed as follows:

Reply: We thank the reviewer for the positive remarks on our work and for the suggestions for further improving the manuscript.

Major Comments:

How to distinguish the convective precipitation and large-scale precipitation? The standard whether is consistent between observation and model?

Reply: In TRMM 3A12 observations, convective and stratiform (i.e., large-scale) precipitation are classified using the brightness temperatures measured by the TRMM Microwave Imager (TMI) radiometer. This is because the local horizontal gradients of brightness temperatures are different in regions with convective and stratiform precipitation. The former is usually characterized by strong gradients of brightness temperature due to large horizontal variations of liquid and ice-phase precipitation, whereas the latter usually has fewer fluctuations of brightness temperature due to relatively weak and uniform updrafts and downdrafts (Kummerow et al. 2001). In global climate models, total precipitation is derived by a process combining resolved grid-scale precipitation explicitly formulated by cloud microphysics schemes (i.e., stratiform or large-scale precipitation generated by the clouds with relatively weak and uniform updrafts and downdrafts) and unresolved sub-grid precipitation formulated by shallow and deep convection schemes (i.e., convective precipitation generated by the clouds with strong updrafts and downdrafts). Although the definitions of convective and large-scale precipitation are not exactly the same between TRMM 3A12 and model simulation, the modeled convective and large-scale (stratiform) precipitation still can be roughly evaluated by using the TRMM 3A12 observations (e.g., Ehsan et al., 2017; Qiu et al., 2019; Chen et al., 2021). We added the description of how the TRMM 3A12 observations derive convective and large-scale precipitation in Lines 232-242 in the revision.

References:

Chen D, Dai A, Hall A. The convective-to-total precipitation ratio and the “drizzling” bias in climate models. Journal of Geophysical Research: Atmospheres, 2021: e2020JD034198.

Ehsan M A, Almazroui M, Yousef A. Impact of different cumulus parameterization schemes in SAUDI-KAU AGCM. Earth Systems and Environment, 2017, 1(1): 3.

Kummerow C, Hong Y, Olson W S, et al. The evolution of the Goddard Profiling Algorithm (GPROF) for rainfall estimation from passive microwave sensors. Journal of Applied Meteorology, 2001, 40(11): 1801-1820.

Qiu L, Im E S, Hur J, et al. Added value of very high resolution climate simulations over South Korea using WRF modeling system. Climate Dynamics, 2020, 54(1): 173-189.

A main problem of this study is: the author mainly focused on the presentation of physical phenomenon, some important interpretations and discussions are unclear or missed. For example, “why the larger particles are easier to be removed by lighter rainfall?” and “what is the relationship between wet scavenging rates and aerosol types?” The reviewer therefore suggests provide some interpretations and discussions in the result section.

Reply: Thanks for the valuable comments. About “why larger particles are easier to be removed by lighter rainfall”, this is because of a combination of higher scavenging coefficients for coarse-mode aerosols in below-cloud scavenging and larger convective-cloud activation fraction prescribed for sea salt and sulfate in the coarse mode according to their hydrophilic properties compared to smaller aerosols. As for “what is the relationship between wet scavenging rates and aerosol types?”, generally aerosols with higher hydrophilicity are easier to be washed out. Please see the reply to the comment below for more details. We added interpretations and discussion in Lines 324-327, 331, and 394-396 in the revision.

What is the difference between in-cloud scavenging and sub-cloud scavenging rate for different aerosol types or precipitation types?

Reply: In CAM5, the aerosol wet removal subroutine treats in-cloud scavenging and below-cloud scavenging. In-cloud scavenging removes cloud-borne aerosol particles (AP) (i.e., aerosols in the cloud droplets) and below-cloud scavenging removes interstitial AP (i.e., aerosols suspended in clear or cloudy air) by precipitation particles through impaction and Brownian diffusion.

For in-cloud scavenging of stratiform clouds, the large-scale precipitation production rates (kg kg^{-1} s^{-1}) and cloud water mixing ratios (kg kg^{-1}) are used to calculate first-order loss rates (s^{-1}) for cloud water (the rate at which cloud-condensate is converted to precipitation within the cloud). These cloud-water first-order loss rates are multiplied by “wet removal adjustment factors” (or tuning factors) to obtain aerosol first-order loss rates, which are applied to activated aerosols within the non-ice cloudy fractions of a grid cell (i.e., cloudy fractions that contain some cloud water). The stratiform in-cloud scavenging only affects the explicitly treated stratiform-cloud-borne AP which are assumed to not interact with convective clouds, and the adjustment factor of 1.0 is currently used. It does not affect the interstitial AP. In-cloud scavenging in ice clouds (i.e., clouds with no liquid water) is not treated. Cloud-borne particles are treated explicitly and activation is calculated with the parameterization of Abdul-Razzak and Ghan (2000), in which larger and more hydrophilic aerosol particles are easier to nucleate into cloud droplets to form precipitation. The large-scale precipitation production rates, which are generated by cloud microphysics processes, also influence in-cloud scavenging in stratiform clouds.

For convective in-cloud scavenging including shallow and deep convection, cloud fractional area, in-cloud cloud condensate mixing ratio and grid-cell mean convective precipitation production (derived from shallow and deep convection parameterizations) are used to calculate first-order loss rates (s^{-1}) for cloud water. Unlike the stratiform cloud-borne AP, the convective cloud-borne AP is not treated explicitly, which is derived by (lumped interstitial aerosols) × (convective-cloud activation fraction) thus only affecting the grid-cell mean interstitial aerosols. The convective-cloud activation is a prescribed parameter that varies with aerosol mode and species. For example, according to different hydrophilic properties, 0.4 and 0.8 are applied to the dust and sea salt of the coarse mode and a weighted average is applied to the coarse mode sulfate and number. Similarly, these cloud-water first-order loss rates are multiplied by “wet removal adjustment factors” to obtain aerosol first-order loss rates. Here, the wet removal adjustment factor for convective clouds is set to 0.4 to avoid too much wet removal produced by convection.

For below-cloud scavenging of the interstitial aerosol, the first-order removal rate is equal to the product (scavenging coefficient) × (precipitation rate). The large-scale precipitation rate (from the cloud microphysics scheme) is for stratiform clouds while the convective precipitation rate (from the shallow and deep convective schemes) is for convective clouds. The scavenging coefficient is calculated using the continuous collection equation (e.g., Equation 2 of Wang et al., 2011), in which the rate of collection of a single aerosol particle by a single precipitation particle is integrated over the aerosol and precipitation particle size distributions, at a precipitation rate of 1 mm h^{-1}. Collection efficiencies from Slinn (1984) and a Marshall-Palmer precipitation size distribution are assumed. The scavenging coefficient varies strongly with particle size, with the lowest values for the accumulation mode. There is no below-cloud scavenging of stratiform-cloud-borne aerosol.

These details were provided in Lines 131-168 in the revision.

References:

Abdul-Razzak, H. and S. J. Ghan (2000). "A parameterization of aerosol activation 2. Multiple aerosol types." J. Geophysical Research-Atmospheres 105(D5): 6837-6844.

Slinn, W. G. N. (1984). Precipitation scavenging, in Atmospheric Science and Power Production, edited by D. Randerson, pp. 472-477, U. S. Dept. of Energy, Washington D. C.

Wang, X., L. Zhang, and M. D. Moran (2011). "Uncertainty assessment of current size-resolved parameterizations for below-cloud particle scavenging by rain." Atmospheric Chemistry and Physics, 10, 5685-5705. doi:10.5194/acp-10-5685-2010.

Specific Comments:

Line 137: What's the physical meaning of K in the Equ.1? The number of days?

Reply: K is a summation index representing an arbitrary day within N_T days. We defined this in the revision.

Line 143: Please check the sentence whether is right? "Graphically, the area under the curve of P in a log-linear plot gives the total amount of mean precipitation". Is it total amount of mean precipitation or total contribution?

Reply: Yes, it is correct because $P(R_i)$ in Eq. (2) is the precipitation amount by the rainfall rates centered at R_i. We make edits in Lines 184-185 to avoid confusion in the revision.

Line 178: Where is d^T

Reply: We removed it in the revision.

Figure 1: add the unit of precipitation in the figure or figure caption.

Reply: The unit mm d^{-1} is added in the figure caption in the revised manuscript.

Figure 2: what's the mean of Y axis in Figure 2? The probability distribution of precipitation amount? Or?

Reply: The Y-axis in the top two rows is the amount of precipitation (i.e., the terms of the left-hand side of Eqs. 2-4) while that in the bottom row is the fractional contribution of convective and large-scale precipitation to the total precipitation.

The Chen et al., (2017) have compared the dust emissions, transport, and deposition between the Taklimakan Desert and Gobi Desert by using WRF-chem, and found markedly difference exists between these two deserts. My question is: accumulated wet removal of dust whether has regional difference over those Desert regions? Is it totally related with the rainfall rates? What's the role of other factors? Such as, snowfall or hail.

Reply: Thanks for bringing our attention to this paper. In Figures 10 and 11, we can see that over dust source regions such as Sahara, the Taklimakan Desert and Gobi Desert, the rainfall rates associated with 50% of the accumulated wet removal of aerosols are similar in the two simulations both smaller than 2 mm d^{-1}. It is because precipitation is scarce over these desert regions, let alone snowfall or hail. Therefore, the dust loadings there are regulated by dust emission, transport and dry deposition. We discussed it and cited this paper in Line 450 in the revision.

Reference:

Chen S. et al. 2017: Comparison of dust emissions, transport, and deposition between the Taklimakan Desert and Gobi Desert. 60 (7), 1338-1355. DOI: 10.1007/s11430-016-9051-0.