Response to Reviewer #2 of acp-2016-831

Dear Reviewer,

Thank you very much for taking your time to review our paper.
I am returning herewith a manuscript revised according to reviewers' comments.
I hope that the manuscript is now acceptable for publication in *ACP*.

[RC]: Referee comment in *Italic*
[AC]: Author comment

General Comment:

[RC] *This paper investigates the strength of aerosol cloud interactions in both models and observations, seeking to examine the sources of the strong lifetime effect in the MIROC5 GCM. The authors show that the precipitation susceptibility for the model shows some similarities to satellite observations, but displays some different characteristics at low and high LWP, which they attribute to the autoconversion scheme in the model. They go on to show how the relationship between liquid water path (LWP) and cloud droplet number concentration (N_d) in the model and observations is very different, changing sign depending on the meteorological environment in the observations but not in the model. They suggest that this means that the precipitation scheme in the model is not capturing some important aspects of the precipitation process.*

The paper is well written and the plots are appropriate. I think that this is a nice way of investigating the model and observational differences. There are a couple of points that I think need clarification, involving the possibility of correlated errors in the retrievals and the validity of the assumptions used in the satellite retrievals along with a few other small points. If these points are addressed, I feel this paper would be suitable for publication in Atmospheric Chemistry and Physics.

[AC] We would like to thank the referee #2 for his/her careful reading our manuscript and for giving positive suggestions.
We tried to revise our manuscript so as to answer to the comments.
Our reply and corrections on individual issues are below.

Specific comments:

[RC1] *Sec 2.2: I am slightly concerned about the use of LWP and N_d from the same instrument and retrieval. Both of these are derived from the MODIS optical depth and effective radius retrievals, which themselves are retrieved together. This means that any errors in the retrieval of the effective radius or the optical depth will propagate through to the LWP and N_d, such that the errors in these derived properties are not independent. If the errors in the effective radius and optical are large enough, this can result in biases in the LWP-N_d relationship (the same thing also applies for the r_e-N_d relationship). Even random errors in the MODIS optical depth and effective radius retrievals would thus be able to generate a LWP-N_d or r_e-N_d sensitivity. These retrieval issues would not be replicated in the model output and could be part of the reason for the model-satellite discrepancy, especially in broken cloud regions.*

[AC1] The retrieval errors in satellite measurements of LWP and N_c for different environmental conditions (e.g., cloud types and rain regimes) are one of the troublesome issues, which do not occur in models. The validity of an adiabatic assumption in their retrieval from satellites is also important issue. Although a use of satellite simulators is the best way for a fair comparison between satellite observations and model simulation, instead that we avoided the issue as much as possible by applying uncertainty thresholds for optical thickness (< 5*) and effective radius (< 1 μm) as described in Sect.

2.2. As a result, 60.2 % of uncertain data were excluded by this procedure. These thresholds are very strict, and are helpful to reduce the N_c uncertainty. Furthermore, we use logarithmic form (i.e., $d \ln X / d \ln N_c$, where $X \in$ tauc, r_e, LWP, R, and P_{conv}) rather than absolute value for constraining cloud and precipitation susceptibilities, which also contributes to reduce a sensitivity of them to the retrieval uncertainties (e.g., Feingold and Siebert, 2009; Sorooshian et al., 2009). We therefore think that the assumptions concerning about the satellite retrievals do not change our results and conclusion so much.

We added notes for these issues in the revised manuscript as follows:
Page 4 Line 17: "We note that satellite data inherently include uncertainties stemming from retrieval assumptions, which are not replicated in the model output. Although it could be a part of reason for discrepancies between the model and observations, this would mostly be canceled when susceptibilities of cloud and precipitation to aerosol loading are evaluated by a logarithmic form.".
*) the submitted discussion paper indicated uncertainty threshold of < 3 for optical thickness, but it was wrong. "< 5" is the right threshold value in this study, and we have corrected in the revised manuscript.

[RC2] *P4 L14: It may also be important that the MODIS derived N_d and LWP depend on the adiabatic assumption, which is not valid in precipitating cases. Is it possible that the relationship in precipitating or broken cloud cases might be influenced by variations in the adiabaticity of the cloud? Again, this assumption would not affect the model results.*
[AC2] The authors agree with this concern. The note about uncertainties from satellite retrievals and assumptions has been added in the revised version as answered in **[AC1]**.

[RC3] *P5 L21: 'P_{conv} can be estimated' - it would make the paper a little more self contained if there was a brief description as to how. It looks like it is also connected to retrievals of the droplet number and cloud water content? Could this also be affected by correlated errors in the retrievals or are these CloudSat number and water content retrievals?*
[AC3] We added more detailed description with some references for derivation of the conversion rate P_{conv} from satellites as follows:
Section 2.2: "To examine the cloud-to-rain conversion process, the conversion rate (P_{conv}) contributed from both autoconversion (collision–coalescence of cloud droplets) and accretion (collision of cloud droplets by raindrops) was derived from the approximation suggested by Stephens and Haynes (2007). This method is established by the continuous collection equation (Pruppacher and Klett, 1997) using observed drop size distributions. P_{conv} was estimated from MODIS LWP and CloudSat mean cloud-layer radar reflectivity $\bar{Z}$ as

$$P_{conv} = c_1 \, \mathrm{LWP} \, \bar{Z} \, H[Z - Z_c], \quad (5)$$

where $c_1 = \kappa_2 / 2^6$ is a coefficient from collection kernel (Long, 1974) with $\kappa_2 = 1.9 \times 10^{11}$ cm^{-3} s^{-1} and sixth moment factor with radar reflectivity. $H[Z - Z_c]$ is the Heaviside step function to exclude the cases that $\bar{Z}$ is less than critical radar threshold Z_c of -15 dBZ for which conversion process is negligible (Matrosov et al., 2004). Although this formulation is based on marine stratocumulus cases from DYCOMS-II measurements (vanZanten et al., 2005), it is applicable for global analysis to study aerosol–cloud interactions (Stephens and Haynes, 2007; Sorooshian et al., 2013) in drizzling light rain cases ($\bar{Z} < 0\ dBZ$). The parameterization and assumptions used in this method (Eq. 5) are also valid for comparison between observations and model simulation (Suzuki and Stephens, 2009). This brings valuable understanding for microphysical conversion processes and its timescales, which matches the scope of our study."
Page 6 Line 4–6: reconstructed in the revised manuscript.

[RC4] *P5 L30: perhaps 'at a higher frequency ... compared to observations'*
[AC4] We have modified, thanks.

[RC5] *P5 L33: 'alternatively ... related to unrealistically light rain.' Just to check, the biases in condensation lead to lower LWP, which in turn leads to more light rain as the autoconversion rate is lower at low LWP?*

[AC5] Yes. This sentence has slightly been modified as follows:
"Alternatively, it is also possible that the model has biases in the condensation processes, which lead to lower LWP and, thus, result in lower autoconversion rate.".

[RC6] *P6 L22: Why is it more likely to find a change in the response of the relationship with precipitation in a high aerosol region? I would have thought that the LWP-N_d relationship is a property of the clouds rather than of the aerosols, which would make it relatively independent of the aerosol level as long as the LWP-N_d relationship is linear.*
[AC6] This study applied to N_c as an aerosol proxy instead of aerosol parameters (e.g., N_a, aerosol index, or AOD), because retrievals of the aerosol information are quite difficult and uncertain when cloud is also present in the retrieved profile simultaneously. Although a use of N_c in observations also partly includes uncertainty due to the assumption of adiabaticity, this would mostly be disappeared when the LWP-N_c relationship is evaluated by a logarithmic form, as answered in **[AC1]**. The validity of the use of N_c as an aerosol proxy is supported by Chen et al. (2014) in observation-based study, and also in a modeling study we have confirmed that the similar results can be obtained even when the model applies AOD or hygroscopic N_a burden as an aerosol proxy instead of N_c. This has been described in the discussion paper in Page 3 Line 1–3 and Page 6 Line 11–12.

The bidirectional responses of LWP (both positive and negative) found in satellite observations in different aerosol concentrations might be related to the concept of "optimal aerosol concentration (N_{op})" recently suggested (Dagan et al., 2015a, 2015b). More specifically, in case of $N_a < N_{op}$, clouds tend to be deeper with larger liquid mass as referred to as cloud invigoration* (e.g., Koren et al., 2014) for increased aerosol loading, whereas the case of $N_a > N_{op}$ would be favorable for cloud suppression due to enhanced entrainment and evaporation. This could lead the bidirectional LWP-susceptibilities, although we cannot mention the exact mechanisms at this stage because N_{op} also depends on both cloud geometric scale and environmental conditions (Koren et al., 2014; Dagan et al., 2015a, 2015b) as well as aerosol types might be involved in.

We have added the above discussion into Sect. 4 of the revised manuscript.

*) We removed the sentence in Page 10 Line 4: "deepening cloud invigoration (Rosenfeld et al., 2014; Koren et al., 2014) and", because the mechanism of cloud invigoration works positive relationship between LWP and aerosol burdens in aerosol-limited conditions (Koren et al., 2014).

[RC7] *P7 L31: How difficult would it be to show the causes of the positive relationship at high stability in precipitating environments? It would help to demonstrate the dominant role of precipitation. At the moment, stability has almost as large an effect as precipitation but this does not fit so neatly into the explanation given (that precipitation is the driving factor in determining the strength of the LWP-N_d relationship).*
[AC7] As referee pointed out, we recognize the importance of atmospheric stability in addition to the precipitation. The cloud dynamical processes that promote evaporation due to turbulent mixing are relatively small in high stability conditions whereas water vapor supply is abundant, which would lead on positive relation between LWP and aerosol loadings over midlatitude oceanic regions. In pristine/clean environments, which is referred to as "aerosol-limited" condition (Koren et al., 2014), aerosols ingested into clouds will tend to store the cloud water but also produce to more rain simultaneously due to abundant water mass. We note that it is just a speculation at this stage, and it might be related to background aerosol number and environmental conditions as discussed in **[AC6]**. We have partly added them in the revised manuscript (Page 8 Line 29–32).

The limitations of current remote sensing techniques, however, CloudSat or polar-orbit satellites measurements cannot capture the exact lifecycle with time-evolution explicitly because they scan instantaneous cloud–precipitation properties (i.e., snapshot), so it must be required high-resolution process modeling using LES or CRM for constraining the detailed mechanisms, as described in the last paragraph of Section 3.3. This will be addressed in future publication.

[RC8] *Fig. 4: I understand that the model version of this figure will be positive almost everywhere, but is there still a pattern in the strength of the relationship that depends on stability or precipitation?*
[AC8] Figure R1 shows the model version of the LWP-susceptibility matrix as a function of rain

regime and stability condition. We used stratiform precipitation rate that corresponds to radar reflectivity estimated from the *Z–R* relationship. As we noted, the model version shows positive LWP-susceptibility in the matrix overall, and the figure does not show the clear correlation of LWP-susceptibility on macrophysical regimes (rain intensity and atmospheric stability).

We further investigated the regional variations with some different environments (Fig. R2). The scatter plots of LWP-susceptibility in different regions from satellite shows positive relationship with LTS, whereas the model does not evident. This error means that the model misses microphysics–dynamics interactions. We added some suggestions for future model improvements, according to the "*short comment*" posted on the discussion forum of our paper. Please see the revised manuscript, Sect. 4.

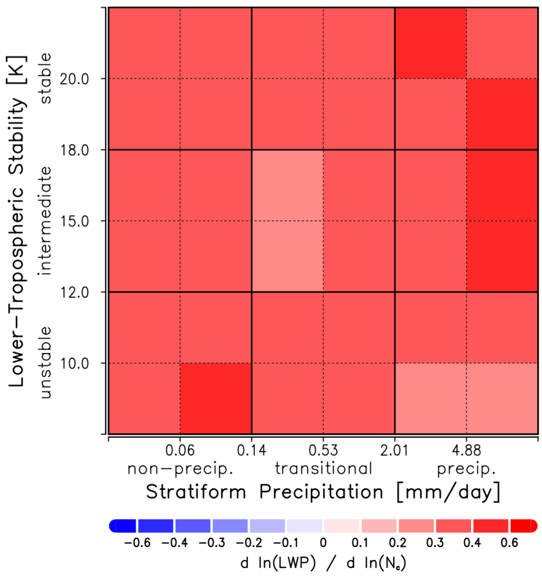

Figure R1. Susceptibility matrix of the LWP response to N_c as a function of stratiform precipitation rate and lower tropospheric stability (LTS) based on MIROC-SPRINTARS simulation.

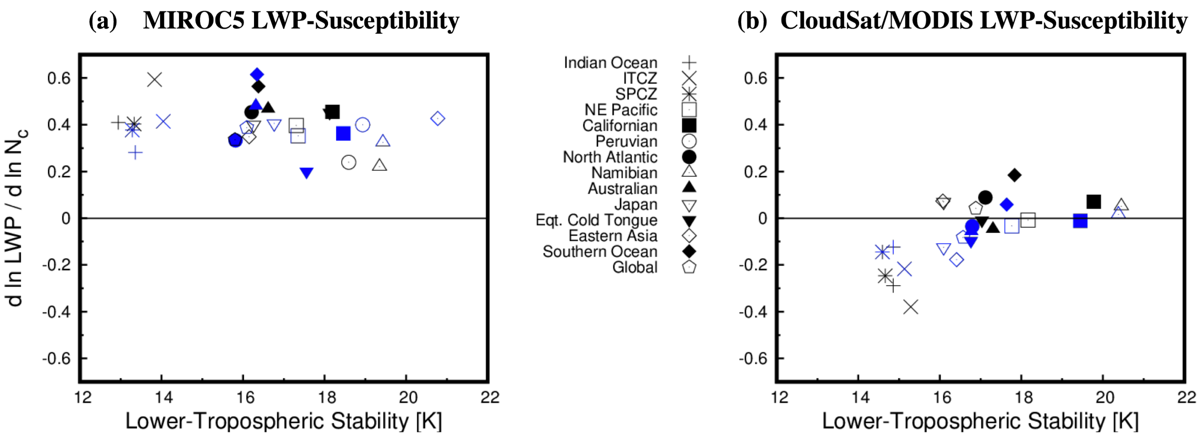

Figure R2. LWP-susceptibility in different regions and rain regimes (black: non-precipitating clouds, blue: precipitating clouds) as a function of LTS from (a) MIROC-SPRINTARS simulation and (b) CloudSat-MODIS satellite observations.

Thank you very much for reviewing our paper.

Sincerely yours,

Takuro Michibata

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