Reply to comments on "Satellite observed indications of aerosol effects on warm cloud properties over Yangtze River Delta of China"

March 28, 2017

We thank the reviewer's thoughtful comments which are helpful not only for this manuscript but also for our future research. Our replies for all the comments are shown below.

Specific comments

1. Comments: (1) Page 1, Line 21: AOD<0.3 and AOD>0.3.

Answer: We made this change (see pg.1 line 23).

2. Comments: (2) Abstract: it would be much helpful if the authors could highlight the overall significance (or implications) of the present study at the end of the abstract (and also in the conclusion section).

Answer: We made this change in the abstract (see pg.1) and in the conclusion section (see pg.25-27).

Page 1, line 35-39: Text was added as:' Overall, the present study provides an understanding of the impact of aerosols on cloud properties over the YRD. In addition to the amount of aerosol particles (or AOD), evidence is provided that aerosol types and ambient environmental conditions need to be considered to understand the observed relationships between cloud properties and AOD.'

Page 27, line 14-16: Text was added as:' In summary, this study will greatly help us to understand the mechanisms of aerosol-cloud interaction and ultimately of aerosol indirect effects over the YRD.'

3. Comments: (3) Page 2, Line 3: change ", and second," to ". Second,"

Answer: We made this change (see pg.2 line 6).

4. Comments: (4) Page 2, Line 10: and clouds, and the aerosol activation efficiency…

Answer: We made this change (see pg.2 line 13).

5. Comments: (5) Page 2, Line 25: and/or

Answer: We made this change (see pg.2 line 28).

6. Comments: (6) Page 3, Lines 19-21: "when using MODIS data" is strange. Rephrase this sentence.

Answer: We made this change (see pg.3 line 23). "Costantino and Breon (2013) and

Jones et al. (2009) found that the aerosol indirect effect is stronger for well-mixed clouds than for well-separated clouds (in well-mixed aerosol and cloud layers are physically interacting, as further explained in Section 2) when using MODIS data." has been changed to "Costantino and Breon (2013) and Jones et al. (2009), using MODIS data, found that the aerosol indirect effect is stronger for well-mixed clouds than for well-separated clouds (in well-mixed aerosol and cloud layers are physically interacting, as further explained in Section 2)." in the revised manuscript.

7. Comments: (7) Page 4, Line 20: Description of the study region
Answer: We made this change (see pg.4 line 25).

8. Comments: (8) Page 5, Figure 1: show in the plot what is the color-coded legend for, AOD?
Answer: Yes, it represents for AOD. We improved the color-coded legend as shown in Figure 1 in the revised manuscript (see pg.5).

9. Comments: (9) Page 6, Line 7: delete "also".
Answer: We made this change (see pg.6 line 17).

10. Comments: (10) Page 6, Line 8-9, "CloudSat was the first mission to fly the first…" rephrase this sentence.
Answer:"CloudSat was the first mission to fly the first…" has been changed to "CloudSat carries the CPR (Cloud Profiling Radar), i.e. the first satellite-based millimeter-wavelength cloud radar to detect the vertical information on different sized cloud droplets" in the revised manuscript (see pg.6 line 13).

11. Comments: (11) Page 7, Table 1: reformat the table, especially the first column.
Answer: We made this change (see pg.7).

12. Comments: (12) Page 8, Line 2: g m-2
Answer: We made this change (see pg.8 line 7).

13. Comments: (13) Page 10, Line 19: replace "CTP" by "CTH"
Answer: We made this change (see pg.13 line 9).

14. Comments: (14) Page 12, Line 20: delete "can".
Answer: We made this change (see pg.15 line 16).

15. Comments: (15) Page 12, Lines 21-22: on the disagreement with the previous findings, can the authors comment on the possible reason?
Answer: Yes, we reanalyzed more data for the considered years and found a clearer relationship between cloud fraction and AOD. Meanwhile, we gave possible reasons for this finding that are not in the disagreement with the previous findings (see pg.15 lines 19-24).

16. Comments: (16) Page 15, Section 3.3.2: what chemical compositions do the smoke aerosols identified by the CALIOP retrievals contain (I presume carbonaceous aerosols)? Please elaborate.

Answer: The CALIOP classification of aerosol subtypes utilizes a depolarization ratio, integrated attenuated backscatter coefficient, surface type and information on whether the layer is elevated or not. The CALIOP algorithm is based on physical properties and does not distinguish aerosol by chemical composition. However, according to previous studies, the smoke particles are observed to strongly absorb solar radiation, particularly at ultraviolet (UV) and visible (VIS) wavelengths. Hence, we can estimate that the aerosols we studied contain carbonaceous aerosols (Mielonen et al., 2009; Ford et al., 2013; Nowottnick et al., 2015) (see pg.18 line 16).

17. Comments: (17) Page 17, Figure 7: the discrimination between low and high RH conditions in the Figure caption (52% and 83%) is inconsistent with the numbers shown in the plot (56%and 85%). Please clarify.

Answer: Now as the analyzed dataset was different, also the result changed. We rephrased the sentence in the revised manuscript (see pg. 20-21). Here, we show cloud properties as function of AOD for only the lowest RH (31%), representing dry conditions, and the highest RH (91%, above the deliquescence point of ambient particles). We made this change (see pg. 20-21).

18. Comments: (18) Page 17, Lines 7-9, "associated with how aerosol particles…": rephrase this sentence.

Answer: "reported to be associated with how aerosol particles…" has changed to" reported to affect the relation between aerosol particles and cloud properties…" in the revised manuscript (see pg.20 lines 14-15).

19. Comments: (19) Page 18, Line 10: define "BL".

Answer: "BL" has been changed to "boundary layer" in the revised manuscript (see pg.22 line 1).

20. Comments: (20) Page 18, Figure 8: delete the second "mixed aerosol-cloud layers under" in the Figure caption.

Answer: We made this change (see pg.20 line 4, see pg.22 line 4, see pg.23 line 15).

21. Comments: (21) Page 20, Figure 9: delete the second "mixed aerosol-cloud layers under" in the Figure caption.

Answer: We made this change (see pg.22 line 4).

22. Comments: (22) Page 20, Conclusions: the conclusion section is too long. It would be better if the authors could concisely summarize the major key findings of this study, other than listing all of the activities and results, in the Conclusion section.

Answer: Yes. We reorganized the conclusion and summarized the major key findings of this study concisely in the conclusion section (see pg.25-27). Here, we present the conclusion section below.

Conclusion

The high level of anthropogenic emissions in Eastern China render this area an important hotspot for studying how cloud microphysical properties are affected by anthropogenic aerosols (Ding et al., 2013). Based on the near-simultaneous aerosol and cloud retrievals provided by MODIS, CALIOP and CloudSat, together with the ERA Interim Reanalysis data, we investigated the effect of aerosols, where AOD is used as a proxy for aerosol loading, on micro-physical and macro-physical cloud properties over the Yangtze River Delta for the years 2007 to 2010. In terms of the relative heights of aerosol and cloud layers, well-mixed and separated clouds are defined. Statistical analysis is used to examine the aerosol effects on cloud properties for these two cases. Besides the aerosol impact on CDR, CF, COT and CTP, also the influence of environmental conditions, such as RH, LTS and PVV, on the relation between cloud properties and AOD has been studied. In addition, the impact of two different aerosol types, dust and smoke, is explored.

The analysis of the COT-CDR and CWP-CDR relationships for well-mixed clouds shows that they are affected by the amount of aerosol. Statistical analysis of the relation between CWP and COT shows an increase in CWP with increasing COT, which is in good agreement with the findings reported by Costantino and Bréon (2013).

Consistent with previous findings, we find that the CDR initially decreases with increasing AOD, followed by an increase when AOD increases over a value of 0.35. This result is consistent with Twomey's hypothesis that increasing aerosol abundance leads to more numerous but smaller cloud droplets at given constant cloud water content. The positive relation between CDR and AOD may be caused by microphysical processes, which is coupled with intense vapour competition and evaporation of smaller droplets as a result of a high abundance of aerosol particles. Also, the analysis of the variation of CF with increasing AOD shows that CF varies with AOD in a way similar to that of CDR. This finding differs from those by Koren et al. (2008) and Small et al. (2011) who observed that an increase in the cloud cover with an increasing AOD, followed by a decrease with higher AOD. COT is found to decrease with an increasing AOD. We argue that the radiative effect and retrieval artefact due to absorbing aerosol might be important factors in determining this relationship. This effect can result in increased cloud evaporation and reduced cloud cover. Meanwhile, CTP tends to increase as aerosol abundance increases, indicating that the aerosol is prone to expand the horizontal extension. In other words, for the well-mixed clouds over the YRD, the CDR becomes smaller with the increase of AOD in moderately polluted conditions (Twomey effect), however, the cloud fraction shows a weak decrease due to the evaporation caused by absorption of aerosols. Therefore in polluted and heavily polluted conditions reduced cloud coverage results in more solar radiation reaching the surface, causing surface heating and thus raises the surface temperature, which then destabilizes the atmosphere. The resulting

advection transports water vapour from the surface to higher levels in the atmosphere, therefore producing more cloud. Meanwhile, CDR becomes larger as a result of the stronger water vapour competition in polluted and heavily polluted conditions. The COT decreases with the increasing values of AOD throughout the AOD range due to the radiative effect and possible retrieval artefacts. With regard to the CTP, it is consistent with the variation of COT, with the cloud getting thinner but with larger cover. So the CTP becomes larger with increasing AOD.

Furthermore, joint correlative analysis of different aerosols and cloud properties reveal that smoke aerosols have a stronger impact on aerosol-cloud interaction due to a stronger absorption of solar radiation by smoke aerosols than by polluted dust. Therefore, we can conclude that absorbing aerosol plays an important role in the aerosol cloud interaction.

Constrained by relative humidity and boundary thermodynamic and dynamic conditions, the variation of cloud properties in response to aerosol abundance is analysed. In general, high relative humidity can promote the formation of larger cloud droplet particles and expand cloud formation, irrespective of vertical or horizontal level. With regard to LTS, stable atmospheric conditions can enhance the cloud cover horizontally. However, unstable atmospheric conditions can be helpful for the formation of thicker and higher clouds. Dynamically, upward motion of air parcels can also facilitate the formation of thicker and higher clouds. Besides the meteorological controls mentioned above, other factors may be important in generating the relations between aerosol and cloud properties, such as temperature advection. These results suggest that effects of ambient meteorological environments need to be considered when exploring the aerosol indirect effect. In summary, this study will greatly help us to understand the mechanisms of aerosol-cloud interaction and ultimately of aerosol indirect effects over the YRD.

23. Comments: (23) This study focuses on the Yangtze River Delta region, but the discussion of results is somewhat general. It doesn't mention what results are unique for the target region. It would be helpful if the authors compare the results in this study with those obtained from other areas in the world, and comment on if any uniqueness of aerosol effects on clouds in the target YRD region.

Answer: Yes. We added some key sentences into the manuscript to mention the unique result for the YRD. For example, the sentence "This outcome is not in agreement with the findings of Koren et al. (2008) and Small et al. (2011)." in the manuscript (see pg.15 line 19) and the sentence 'This study shows that the COT-CDR and CWP-CDR relationships are not unique, but affected by an atmospheric aerosol loading.' in the abstract (see pg.1 line 20-21).

References

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