Reply to comments on "Satellite-based estimate of the variability of warm cloud properties associated with aerosol and meteorological conditions"

October 30, 2018

We would like to express our appreciation to the reviewer for the detailed and valuable comments which helped us a lot to improve the manuscript. Our replies to all comments are shown below.

Comments

1. Comments: (1) Page 4, Line 20: How is the possibility of vertical segregation of cloud and aerosol accounted for? For example, the presence of a lofted aerosol layer in the same scene as the low clouds?

Answer: Caution is warranted in investigating the satellite-derived relations between aerosol and cloud properties. With MODIS we cannot resolve the height of aerosol and cloud layers, or detect aerosol above clouds. However, the physical and optical properties of clouds and aerosol are quite different and these are used to separate aerosols from clouds. These tests will not work for lofted aerosol layers above clouds because the cloud reflectance overwhelms that of aerosols. Some other sensors rather than MODIS have specific instrument characteristics that allow for this separation. Firstly, as we know, CALIPSO and CloudSat can provide the height of aerosol layer and cloud layer, however, the relatively low number of MODIS-CALIPSO coincidences limits the further binning of the data required to investigate this issue. Secondly, when it comes to the occurrence of cloud contamination in the AOD dataset, this is a universal and one of the most difficult problems in aerosol retrieval. Cloud detection is usually not perfect, so that undetected, or residual, clouds contaminate the retrieval area which leads to AOD overestimation and in turn affects the relation between aerosol and cloud properties (e.g. Sogacheva et al., 2017). A study by Mei et al. (2016), comparing their MERIS cloud mask with two independent data sets, shows that on the order of 70-90% of the cases are correctly classified as cloud free. This result is in good agreement with that from a dedicated study on a consistency between aerosol and cloud retrievals from the same instrument which showed that about 20% of the pixels may be mis-classified (Klueser, 2014). In this study, the samples with AOD values greater than 0.8 were excluded as a rough attempt to exclude cloud-contaminated AOD to reduce the uncertainty in the observed ACI. As reported by Yuan et al. (2010), the potential artefact mentioned above does not seem to be the primary cause for the observed relationship between aerosol and cloud parameters. Further investigations are needed to fully analyze and explain the observed

phenomena.

2. Comments: (2) Section 3.2: Should this not include a sentence on how the significance of results is to be determined? The results table speaks of statistical significance but I'm not clear how this is measured.

Answer: Yes, we agree. We made this change in the revised manuscript (see page 6, line 21-23).

Page 6, line 21-23: Text was added as:' Student's t test is used to determine whether two data sets are significantly different from each other. The marker ** at the top right corner of symbol "+" (or "-") denotes that the difference between a change in cloud property and zero is significant (at 95% confidence level).'

3. Comments: Section 4.1: I was under the impression from section 3.1 that the difference in cloud properties at time=0 had been removed by re-sampling the data. I think the relationship between sections 3.1 and 4.1 needs to be developed with the lay reader in mind.

Answer: Normalised histograms of cloud properties for the high and low AOD populations are made for the whole region (Section 3.1), because the data volume based on each 1° x 1° location is relatively small. However, the difference between the cloud properties for low and high AOD at the start time is based on each 1° x 1° location (Section 4.1). So the difference of the cloud properties between the low and high AOD at the start time is not zero. In order to make the reader understand, text was added as follows.

page 5 line 37-39 and page 6 lines 1-2: Text was added as: 'Note that here and in the following sections, normalised histograms of cloud properties for the high and low AOD populations are made for the whole region (Section 3.1), because the data volume based on each 1° x 1° location is relatively small. However, the difference between the cloud properties for low and high AOD at the start time is based on each 1° x 1° location (Section 4.1). So the difference of the cloud properties between the low and high AOD at the start time is not zero.'

Page 9, line 14-16: Text was added as: 'Although normalized histograms of meteorological parameters are made for high and low AOD conditions at the start time, the normalization described in Sect. 3.1 is based on the whole region. Differences in meteorological conditions may still occur between each 1° x 1° grid cell.'

Meanwhile, in order to consider the effect of meteorological conditions on the relationship between aerosol and cloud further, we analyze the meteorology of the different regions in section 4.2 (see page 9-10). This new section 4.2 "The meteorology of the four target regions" reads:

4.2 The meteorology of the four target regions

The meteorological and aerosol effects on clouds are reported to be tightly connected, and this connection must be accounted for in any study of aerosol-cloud interactions (Stevens and Feingold, 2009; Koren et al., 2010). Although normalized histograms of meteorological parameters are made for high and low AOD conditions at the start

time, the normalization described in Sect. 3.1 is based on the whole region. Differences in meteorological conditions may still occur between each 1° x 1° grid cell. In this study, we analyze the meteorology of the different regions, in support of the interpretation of the regional variation of the relationships between aerosols and clouds.

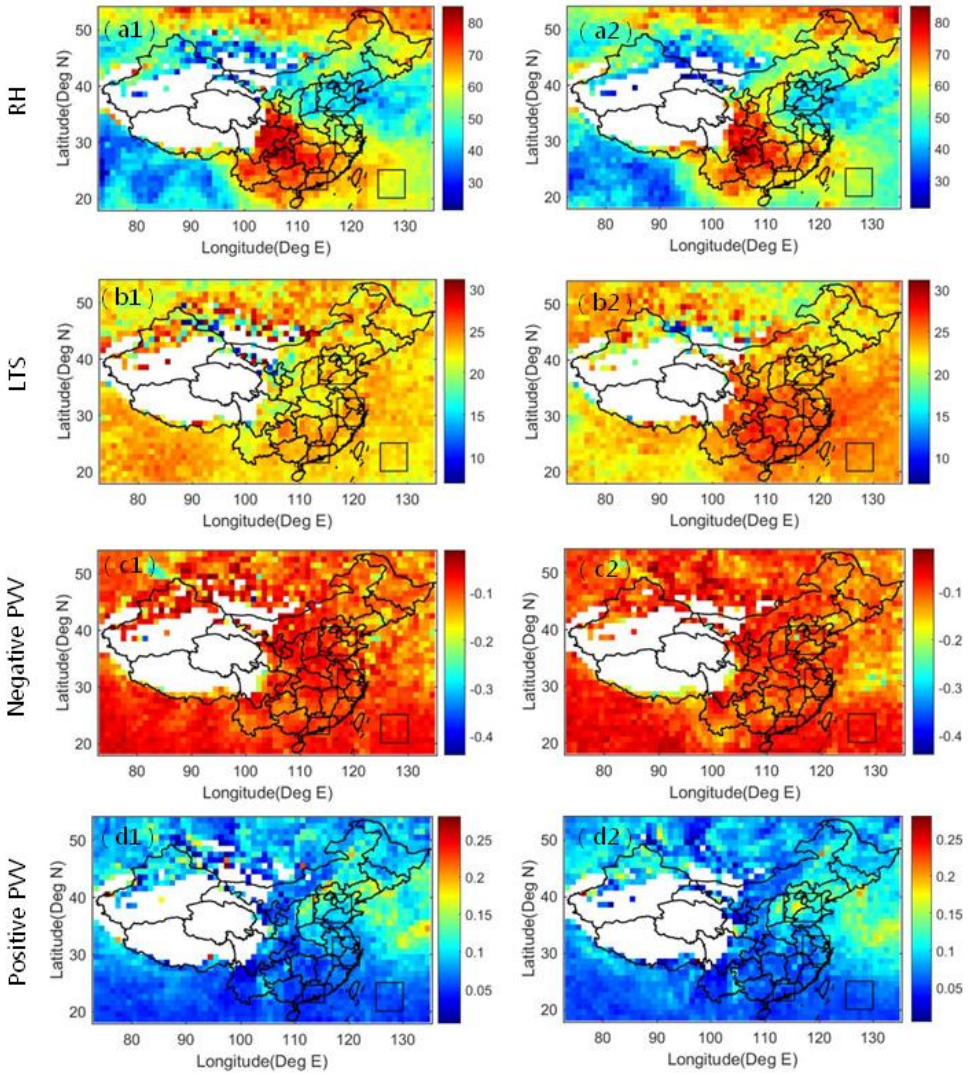

Figure 4 Spatial distributions of meteorological parameters (top to bottom: RH, LTS, positive PVV and negative PVV) at the start time of the timestep (MODIS/Terra) for low AOD conditions (left, a1-d1) and for high AOD conditions (right, a2-d2). All the data are averaged over all years between 2008 and 2017.

The spatial variations of the aerosol and cloud properties over the four regions, averaged over the years 2008-2017, are shown in Fig. 4. Over the urban clusters, we can see an increasing north–south pattern in RH and LTS, with the lowest values found in the PRD. For the negative PVV, the spatial distributions for the low and high AOD situations are remarkably similar, with the highest values over the BTH and decreasing toward the south to near zero over the PRD. In contrast, the positive PVV is smallest over the BTH, with little variation over the study area. Overall, the meteorological parameters over the YRD and PRD are similar to those over the ECS, irrespective of the AOD. Furthermore, the LTS is significant larger in the high AOD

conditions for all the four regions. Zhao et al. (2006) proposed that the enhancement in the atmospheric stability tends to depress upward motion and precipitation, leading to an increase in aerosol particles. The spatial distributions of both positive and negative PVV in the low AOD conditions are similar to those in the high AOD conditions.

4. Comments: Page 9, Line 31: I'm not sure what this sentence means – either the ECS is your marine study area or it isn't. I would caution against using parentheses in the way used in this sentence, because it is well - recognised to make the sentence much harder to comprehend whilst reading. The writer should be aiming to help the reader assimilate the information at normal reading speed, not to slow them down with internal opposites that require going back and forth over the sentence repeatedly.

Answer: Following reviewers' comments, we use collection 6.1 data and reanalyze all the data for the whole acquisition period between 2008 and 2017, rather than collection 5.1 data from 2008 to 2011. As a result, the data base was expanded and provides more cases. We have included this information throughout the revised manuscript (all the figures were changed/modified in this respect). So, we reorganize the sentences in the section (see page 11, line 16-17) and do not use parentheses in the way in this sentence throughout the revised manuscript.

"Over the ECS, in low AOD conditions, CDR decreases during the timestep while COT and CWP increase (Figure 4). For high AOD conditions, the variations of the cloud properties (CDR, COT and CWP) during the timestep are similar to those for low AOD conditions (Figure 5). Furthermore, it appears that COT and CWP increase more at low AOD than at high AOD. Having a closer look at the CF/CTP variation in both low and high conditions over ocean, we can find that CF decreases (CTP increases) in low AOD conditions and CF increases (CTP decreases) in high AOD conditions over ocean, albeit not over ECS. " has been changed to "Over the ECS, in both low and high AOD conditions, CDR, CF and CTP decrease during the timestep while COT and CWP increase (see Figure 5). " in the revised manuscript (see page 10). Also, as we merged section 4.2 with section 4.3 (as new Section 4.3, see pages 10-15), more discussion has been shown in section 4.3 of the revised manuscript (see page 14-15).

5. Comments: Page 10, Line 1: is the other "significant difference" one or two differences? The sentence seems to suggest that CF and CTP co-vary, which in turn suggests they need not have been studies separately.

Answer: As mentioned above, due to the larger data set, the variation of cloud properties to the aerosol environment has become more clear. This is shown throughout the revised manuscript (all the figures were changed/modified in this respect). We reorganized the sentences in the section (see page 11, line 18-27).

The paragraph "In general, the variations in cloud properties over land are similar to those over ocean for both low and high AOD conditions over 3 hours. Two significant differences are found between land and ocean areas. One is that CDR increases over

land but decreases over ocean after the timestep, another significant difference is that CF decreases (CTP increases) for low AOD condition but CF increases (CTP decreases) for high AOD condition over ocean after the timestep, whereas CF increases (CTP decreases) for both low and high AOD conditions over land after the timestep. We can conclude that the variation of cloud properties after 3 hours depends little on the initial AOD over land, even though differences exist among the urban clusters. The increase in afternoon cloud fraction over land is consistent with previous studies concluding that continental warm clouds are likely to be well developed (Wang et al., 2014; Kourtidis et al., 2015). The decrease in afternoon cloud cover over ocean confirms that the largest cover for marine clouds is reached early in the morning (Meskhidze et al., 2009). Table 2 summaries the differences in cloud properties between the Aqua and Terra overpasses for high and low AOD conditions over land and ocean during the time period 2008-2011, respectively.” **has been changed to** “In general, the variations over 3 hours in COT and CWP over land are similar to those over ocean for both low and high AOD conditions. Another significant similarity is that CF decreases for low AOD conditions over land and ocean during the 3h timestep. Having a closer look at the CF variation over the YRD and PRD, we see that CF increases in high AOD conditions during the 3h timestep. This implies that the variation of CF may depend on the initial AOD conditions. The decrease in afternoon cloud cover over ocean confirms that the largest cover for marine clouds is reached early in the morning as was also concluded by Meskhidze et al. (2009). Meanwhile, a significant difference is found between land and ocean areas, i.e. in high AOD conditions CDR increases over land but decreases over ocean during the 3h timestep. Table 2 summaries the differences in cloud properties between the Aqua and Terra overpasses for high and low AOD conditions over land and ocean during the time period 2008-2017.”

6. Comments: Figures 3-5: might it be possible to shade the graphs on the right-hand columns of these figures to show when changes are self-consistent from a microphysics or cloud dynamics point of view?

Answer: We do not understand what the reviewer means with “self-consistent from a micro-physics or cloud dynamics point of view”. Hence we have not added a shading to these graphs.

7. Comments: Section 4.3 and Figure 6: This reader is left feeling that there is very little added value in this section. The statistics all look close to zero and noisy and the text doesn’t make any very strong statements over and above those from previous sections. Is this section really necessary?

Answer: As mentioned above, in response to the reviewers’ comments, we use collection 6.1 data and reanalyze all the data for the whole acquisition period between 2008 and 2017, rather than collection 5.1 data from 2008 to 2011. Therefore, the variation of cloud properties to the aerosol environment has become more clear. This is explained throughout the revised manuscript (all the figures were changed/modified in this respect). Furthermore, Section 4.2 was merged with section 4.3 (as new

Section 4.3, see pages 10-15), explicitly examining the difference of cloud properties in relation to aerosol environment. Also a new Section 4.2 was added (see response to question 3) to describe the meteorology of the four target regions, in support of the interpretation of the regional variation of relationship between aerosol and cloud (see page 9-10).

8. Comments: Section 4.4 is too definitive considering the uncertainty shown in Figure 7. I also missed a tie-back to basic cloud physics – how is the reader to interpret the effect of aerosol concentration on cloud parameters when the air is descending and cloud formation therefore suppressed? Some context is required here to help the reader who is not familiar with such analyses.

Answer: Yes, we made this change (see page 16 lines 13-16). "The presence of upward motion, as indicated by negative PVV, can enhance the interaction between aerosol particles and clouds as it makes the ambient environment favorable for cloud formation, and vice versa (Jones et al., 2009)." has been changed to "The presence of upward motion, as indicated by negative PVV, can enhance the interaction between aerosol particles and clouds as it promotes vertical mixing of the aerosol particles and thus reach the cloud condensation level where they grow into cloud droplets (Jones et al., 2009)." As the variation of cloud properties to the aerosol environment has become more clear, we also reorganized the sentences in the Section 4.4 (see pages 16-17).

Minor comments

1. Comments: (1) Page 2, line 36: delete 'desperately'

Answer: Yes, we made this change (see page 3, line 1).

2. Comments: (2) Page 6, Figure 2: would plotting on log axes help the differences to be visible? For the caption: presumably this is an example of a PDF of CF?

Answer: We use collection 6.1 data and reanalyze all the data for the whole acquisition period between 2008 and 2017, rather than collection 5.1 data from 2008 to 2011. So, Figure 2 has also been changed and the differences can be seen easily (see page 6).

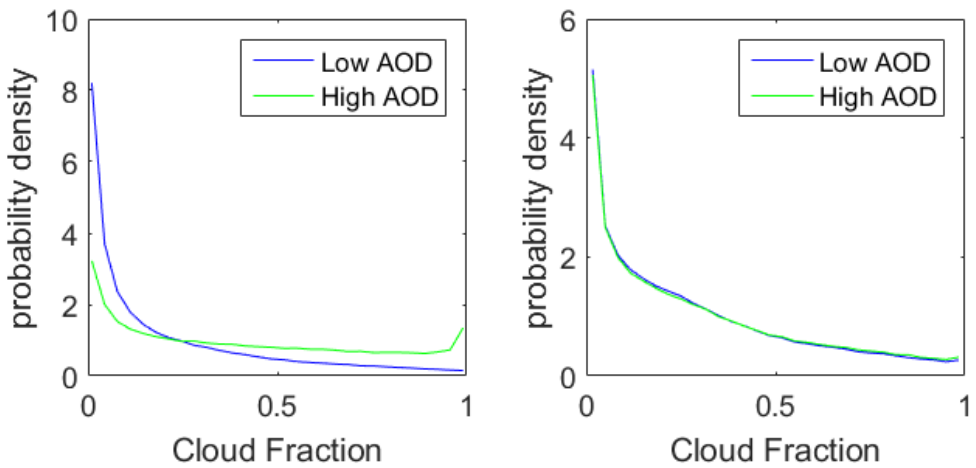

Figure 2. An example of the probability density distribution of warm cloud fraction (CF) for low and high AOD conditions. (a) there is a strong link between AOD and CF before histogram normalization, (b) the link is reduced after histogram normalization.

3. Comments: (3) Page 6, line 12: "Cloud_X (where X=CF, COT, CWP, CDR or CTP)" – just for extra clarity.
Answer: Yes, we made this change (see page 6, line 11).

4. Comments: (4) Page 6, line 13-16: "_Cloud_X[High AOD]" should be overbarred in text as in equation.
Answer: Yes, we made this change (see page 6, line 12).

5. Comments: (5) Page 9, line 27: plot should be plotted.
Answer: We use collection 6.1 data and reanalyze all the data for the whole acquisition period between 2008 and 2017, rather than collection 5.1 data from 2008 to 2011. So, Figure 4 and 5 have been changed to Figure 5 and 6 (see page 12-13).

6. Comments: (6) Page 15, line 12: "when PVV is positive" is more consistent.
Answer: Because the analyzed dataset was different (MODIS C6.1 versus older versions), the result also changed. We rephrased the sentence in the revised manuscript (see page 16).

7. Comments: (7) Page 17, line 1: the statistical methods are not described anywhere that I can see.
Answer: Page 19, lines 8-9: 'Data over these four study areas were collected for the years 2008 to 2017, and analyzed using statistical methods.' was changed to ' Data over these four study areas were collected for the years 2008 to 2017 and analyzed in statistical sense.' Here, we mean with statistical sense that we looked at the 10-year mean properties rather than at individual case studies.

References

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