Review of "Multi-satellite aerosol observations in the vicinity of clouds" by Tamás Várnai, Alexander Marshak, and Weidong Yang

Anonymous Referee #1

This paper analyzes MODIS and CALIPSO observations of aerosol optical property variability in the vicinity of clouds. As stated in the manuscript introduction, this is an important problem to better understand aerosol-cloud interactions and the direct radiative effect of aerosols as well as to improve satellite retrieval algorithms, which need to account for the variability in aerosol properties near clouds. The topic of this paper is thusly relevant and within the scope of Atmospheric Chemistry and Physics. Previous studies, which are summarized in the introduction, show that aerosol properties are consistently observed to change in the vicinity of clouds, which is caused in part by true changes in aerosol properties and in part due to instrument effects. Crucially, a consensus has not been reached in the literature on the relative contributions of each of these components within the observations.

The authors therefore present a novel method to partition MODIS observations of aerosol variability near clouds into separate components and assess the contributions of each. MODIS observations of near-cloud aerosol changes depends on particle changes in the near-cloud environment, 3-D radiative effects, instrument blurring, and "other" reasons not identified. Two of these components in particular are estimated in a novel manner in this paper. First, the authors use CALIOP observations of enhanced backscatter near clouds to describe particle changes in the near-cloud environment under the valid assumption that CALIOP is not affected by the 3-D effects or instrument blurring which in turn allows them to estimate the portion of the MODIS reflectance enhancement ascribed to particle changes and the reflectance enhancement due to the other effects. Secondly, the contribution of 3-D radiative enhancements due to molecular scattering are estimated using a Monte Carlo model with the MODIS cloud mask along the CALIOP ground track. Though this model does not include the effects of aerosol and surface scattering, it does quantify the minimum contribution due to 3-D radiative effects, which is very useful and enlightening approach.

The conclusions drawn by the analysis – that nearly two-thirds of near-cloud enhancement is due to changes in aerosol properties and the remaining contribution is due mostly to 3-D radiative effects and instrument blurring – is an important step forward in understanding MODIS aerosol observations near clouds. These conclusions are based on valid assumptions and methods. The text is clearly written throughout with well-constructed and appropriate supporting figures. Most of my comments below are to encourage the authors to provide a few more details to ensure that the paper completely describes the methods in a manner that is easily reproducible by other researchers. These additions can be easily implemented by the authors and should not inhibit consideration for publication. It is a very solid paper in its current form.

Altogether, this is a strong paper that makes important advances in the understanding of observations of aerosol near clouds. Based on the thoroughness of the analysis, novelty of approach, and importance of results I recommend this paper for publication in Atmospheric Chemistry and Physics after the authors please address my comments.

Thank you indeed for the thoughtful review and helpful suggestions!

Specific comments:

1. Attenuated backscatter is being used, but is called backscatter. For clarity, explicitly state that attenuated backscatter is used where applicable.

Following the suggestion, we included the word “attenuated” into five sentences.

2. State which versions of CALIPSO and MODIS data are being used.

We now mention in Section 3 that we use CALIOP Version 3 and MODIS Collection 5 products throughout the study.

3. Page 32041 (lines 5-6): I suggest adding [Su et al., 2008] to this list of references as it is the first paper (or at least one of the first papers) to average lidar data as a function of distance to cloud.

We added the reference as suggested.

4. Page 32044 (line 6): Aerosol number concentration can increase near clouds due to detrainment of cloud-processed particles into the cloud-free environment. This should be mentioned as another cause of differences in aerosol near clouds versus far from clouds. What impact would this have on the spectral dependence explanations of figure 2?

We included into Section 1 the detrainment of cloud-processed particles as another mechanism for near-cloud changes.

In cases when cloud processing increases the concentration of small particles near clouds (e.g., through SOA formation in clouds), it likely reduces the degree to which swollen aerosols and undetected cloud drops counteract 3D bluing when $R_{0.65}$ increases in Figure 2c (second to last sentence in Section 3). On the other hand, in cases when cloud processing works mainly by small CCNs merging into fewer large aerosols through the collision-coalescence of cloud drops, it likely helps swollen aerosols and undetected cloud drops in counteracting 3D bluing.

Ultimately, the influence of large particles near clouds for large $R_{0.65}$ appears to yield similar $R_{0.47}$ values close to and far from clouds (Figure 2c). Although cloud processing likely affects the magnitude of near-cloud particle size increase, the second to last sentence of Section 3 discusses the overall behavior in a qualitative sense and so it does not appear necessary to change it.

5. Page 32040 (line 22): Instrument blurring should be briefly defined somewhere. The Meister and McClain 2010 reference does not call the effect being described as “instrument blurring”.

To connect “instrument blurring” to the “stray light contamination” of Meister and McClain (2010), we expanded a sentence in Section 1 so it now includes “instrument blurring caused by stray light contamination (Meister and McClain, 2010)”.

6. Figure 1 a-b caption: Units should be included for integrated backscatter coefficients.

We added the units to the figure axis label.

7. Figure 1c: This histogram using the MODIS cloud mask to determine distance to the nearest cloud looks a lot like the histogram in [Varnai and Marshak, 2011, Fig 1(a) inset] that uses CALIPSO to determine the distance to the nearest cloud. Perhaps this should be mentioned as a way to further support the decision to use the MODIS cloud mask for the analysis rather than the CALIPSO cloud mask.

We see the reviewer’s point that Figure 1c looked a lot like the histogram in Várnai and Marshak (2011). Since the earlier study’s histogram justifies the 5 km threshold for Figures 1a and 1b, we removed Figure 1c as it didn't seem essential to this paper.

8. Figure 1 a-b: Why integrate everything below 3 km in altitude? The method should be better explained. If the cloud exists between 0.5 – 2 km, then why is data above 2 km and below 0.5 km included in the integration? Does this assume that the transition zone around clouds occurs the same vertically as it does horizontally; i.e. the rates of change in color ratio and attenuated backscatter are the same vertically as they are horizontally?

We agree that considering all altitudes below 3 km means that we include data for which the proximity of clouds does not make any difference. For example, Figures 3c and 3d in Várnai and Marshak (2011) show that the proximity to clouds does not affect altitudes above cloud top. Fortunately, including data from these altitudes does not change the near-cloud trends in vertically integrated values. (Including these altitudes shifts integrated backscatters and color ratios by constant values independent from the distance to clouds.) Considering altitudes not affected by clouds does not assume that the transition zone around clouds would be the same vertically and horizontally, i.e., that the rates of change in color ratio and attenuated backscatter would be the same vertically as and horizontally.

We prefer including all altitudes below 3 km for several reasons:

- Uncertainties in the cloud top altitudes derived from MODIS data outside the CALIOP track would risk excluding data at altitudes that are in fact influenced by nearby clouds.
- Since the base of thick clouds is often not known accurately even along the CALIOP track, trying to exclude altitudes below cloud base would risk excluding cloud-impacted data.
- Cloud-related processes may impact aerosol populations even below cloud base. For example, aerosols can swell in humid air even below cloud base, while rain or virgas from recently dissipated clouds may have washed out

aerosols or brought undetected cloud droplets or cloud-processed aerosols to altitudes below cloud base.

Let us also mention that MODIS data inherently includes the impact of altitudes not affected by clouds.

9. Section 2: What was used to cloud-clear the CALIOP data? The CALIOP vertical feature mask? The MODIS cloud mask? Please be specific.

We included the following sentence into the caption of Figure 1: "For the nighttime dataset analyzed in this figure, low clouds are detected using the Version 3 CALIOP vertical feature mask, and are defined as clouds for which CALIOP indicates a cloud top altitude of less than 3 km."

We also included into Section 3, at the discussion of Figure 2, the following sentence: "This figure and all subsequent figures use daytime data and the MODIS cloud mask that can detect clouds even outside the CALIOP track."

- Page 32044 (line 15): Clarify that it is horizontal resolution being degraded, as in: "degraded from 333 m to 1 km horizontal resolution."

Done.

- Page 32045 (line16): What are the vertical limits of integration of the backscatter? Is the entire column from 40 km to the surface integrated?

To clarify this, we expanded the wording to "CALIOP 532 nm backscatter vertically integrated below 3 km altitude".

- Page 32045 (line16): Though it is a matter of preference, the most commonly used symbol for integrated backscatter is gamma instead of beta. Consider changing symbols to γ^P instead of β^P to be more consistent with other lidar literature [Platt, 1973, p. 1197] and CALIPSO documentation.

We see the reviewer's point that gamma is often used for lidar backscatter, and that we should aim at consistency with earlier studies. Unfortunately earlier studies did not all use the same notation, and so we prefer keeping beta for consistency with some other related studies (e.g., Várnai and Marshak 2011, Yang et al. 2012)

- Page 32045 (line24): More details should be given in the text on how the contributions of surface reflection and Rayleigh scattering were removed from the 0.55 μm reflectance values. Is there a reference you could also include describing the Collection 6 algorithms which consider wind speed? Perhaps Levy et al. [2013]?

We included the recommended reference and expanded the explanation, which now says: "The combined surface and Rayleigh contributions are estimated as the reflectances expected for completely aerosol- and cloud-free columns. These expected reflectances are obtained from the upcoming Collection 6 version of the operational MODIS aerosol retrieval algorithm, which considers wind speed values from the GEOS-5 reanalysis (Levy et al., 2013)."

- Figure 3a caption: Please list the latitude/longitude domains used for the four regions.

We included the following sentence into the figure caption: The coordinates of the four regions are as follows. 1: (5-20°N, 15-45°W), 2: (25-45°N, 55-80°W), 3: (15-45°N, 110-140°E), 4: (0-20°S, 20°W-10°E).

- Page 32046 (line 10): The additional MODIS near cloud enhancement could also be caused by cloud contamination; i.e., a pixel identified as clear when it in fact contains cloud. How well does MODIS cloud identification perform for these low level clouds and how would it impact the MODIS near-cloud enhancements? This should be mentioned in somewhere in the paper (not necessarily here).

To clarify that the extra enhancement does not come cloud detection being less effective for MODIS than for CALIOP, we added a note in parenthesis so the sentence now says "Because changes in particle populations should cause similar relative enhancements in particle scattering for CALIOP and MODIS (both the CALIOP and MODIS curves are obtained using the MODIS cloud mask), most of the extra enhancement likely arises from 3D radiative processes and instrument blurring. "

- Figure 4: The vertical axis shows the relative enhancement in terms of R^P when both R^P and β^P are plotted (or if you change symbols as suggested in comment 12, γ^P). Change the vertical axis label or figure caption to accurately explain what is plotted. Maybe place the relative enhancement equation in the caption using the variable x where x can be either R_P (red curve) or β_P (blue curve).

We added to the figure caption the sentence "Relative enhancements (*RE*) are calculated using the equation $RE = 100\ (X - X_{20\ km}) / X_{20\ km}$, with X being R^p or β^p for the two curves."

- Page 32046 (lines 17-19): I do not think the calculation of the percent by which MODIS enhancements exceed CALIPSO enhancements in Figure 4, yielding 40-45%, is correct. The closest distance to cloud in Figure 4 shows a CALIOP relative enhancement of 60% and a MODIS relative enhancement of about 85%. Since these are both relative enhancements normalized to 20 km, MODIS relative enhancement exceeds that of CALIPSO by 25%; i.e. 85% − 60% = 25%. I believe the authors calculate the percent difference of the enhancements using (85% − 60%)/60% = 0.42, or 42%. However, I think that MODIS enhancements exceed CALIOP enhancements by the difference of relative enhancements in Figure 4 which is around 15-25% in the nearest 5 km. Can the authors please clarify why the difference should not be used? Additionally, if the difference should be used, should lines 18-19 read ". . .explain roughly three-quarters" as opposed to "two-thirds"?

Indeed, we use the percent difference of the enhancements, e.g., (85% − 60%)/60% = 0.42, or 42%. We prefer mentioning the relative difference instead of absolute difference, because the absolute difference changes with distance, whereas the relative difference remains fairly constant.

However, to make things more clear, we changed this sentence to: "Within 5 km from clouds, however, MODIS enhancements significantly exceed CALIOP enhancements: The relative difference between the two enhancements near clouds is about 30% of MODIS enhancements."

The next sentence was changed to "This implies that changes in aerosols and undetected cloud particles explain roughly two thirds (70%) of MODIS reflectance enhancements near clouds, with the remaining third likely coming from 3D and instrumental effects." While 70% is not far from three quarters either, we prefer using two thirds as a rough descriptor because, as now discussed in Section 5, the 70% is more likely to be an overestimate than an underestimate.

- Page 32047 (line 1): The enhancement in cloud fraction leads to a 0.05 increase in clear sky optical depth not cloud optical depth according to [Chand et al., 2012]. This should be corrected.

Done.

- Page 32047 (line 19): Please include more details on how the 15-25% enhancement due to the simulated 3D component was calculated. Is the range due to the varying solar zenith angles? Do we need to know the average 0.55 μm reflectance at 20 km? Include enough information so the reader can take the numbers in Figure 5a-b and confirm a 15-25% enhancement.

We clarified this issue by changing the sentence to "Nevertheless, the results in Figure 5a show that the simulated component of 3D enhancement explains 15-20% of the observed near-cloud enhancements, as the simulated values (green curve) are about 15-20% of the observed values (red curve). " The variations between 15-20% occur for various distances. This is shown later in Figure 6c.

- Page 32048 (lines 5-6): The text says the black line shows the nadir reflectance over the median reflectance at 20 km away from cloud. The word "over" sounds like you are taking a ratio when you are in fact taking the difference between the nadir reflectance and median reflectance at 20 km away. Change the language here to better describe the figure.

We expanded the sentence to "The black line in Figure 6 indicates the observed increase in median MODIS 0.55 μm nadir reflectance—that is, the difference from the median reflectance observed 20 km away from clouds ($R_{20\ km}$ = 0.061).

- Page 32048 (line 6): Include the median reflectance observed 20 km away from clouds so the reader can calculate percent changes.

Done (see above).

- Figure 6a caption: This is an important figure. It would be worth re-iterating that the solar zenith angle of the MODIS observations was less than 30 degrees (is that right?). Also, consider making the font size larger on the figure itself.

The solar zenith angle was not limited to 30° or less; the figure is based on the entire dataset used in earlier figures and includes all solar zenith angles that occurred between 60°N and 60°S at the time of observations.

Typographical comments:

1. Page 32051 (line 28): Change "are important in the at least half of all clear areas" to "are important in at least half of all clear areas".

We prefer keeping the word "the", as without it some readers might think that we consider only clear areas that lie in the vicinity of clouds and then we take at least half of these areas—whereas we refer to at least half of all clear areas.

References:

Chand, D., R. Wood, S. J. Ghan, M. Wang, M. Ovchinnikov, P. J. Rasch, S. Miller, B. Schichtel, and T. Moore (2012), Aerosol optical depth increase in partly cloudy conditions, Journal of Geophysical Research, 117(D17).

Levy, R. C., S. Mattoo, L. A. Munchak, L. A. Remer, A. M. Sayer, and N. C. Hsu (2013), The Collection 6 MODIS aerosol products over land and ocean, Atmos. Meas. Tech. Discuss., 6(1), 159-259.

Platt, C. M. R. (1973), Lidar and Radiometric Observations of Cirrus Clouds, Journal of the Atmospheric Sciences, 30(6), 1191-1204.

Su, W., G. L. Schuster, N. G. Loeb, R. R. Rogers, R. A. Ferrare, C. A. Hostetler, J. W. Hair, and M. D. Obland (2008), Aerosol and cloud interaction observed from high spectral resolution lidar data, Journal of Geophysical Research: Atmospheres, 113(D24), n/a-n/a.

Varnai, T., and A. Marshak (2011), Global CALIPSO Observations of Aerosol Changes Near Clouds, Geoscience and Remote Sensing Letters, IEEE, 8(1), 19-23.