***Interactive comment on*** **"Multi-satellite aerosol observations in the vicinity of clouds"** ***by*** **T. Várnai et al.**

**Anonymous Referee #2**

This paper combines data from the passive MODIS imager, and the active CALIOP lidar, in attempt to better understand the observed reflectance enhancement near clouds. The transition zone between clouds and cloud-free atmosphere is explored using one yearlong global data from the two satellites, and two radiative transfer models.

In the first part of this study, following the analysis of CALIOP color ratio, the particulate matter suspended in the atmosphere (aerosol and 'undetected' cloud droplets) is found to be larger when comparing the closest 5 km to the nearest low cloud (below 3 km) with the rest of the atmosphere, above oceans. Then, a comparison between MODIS and CALIOP reflectance biases in the closest 20 km from cloud provides indication of the 3D effect contribution to the total observed reflectance bias near clouds, for four different regions and aerosol types. Additional 3D Monte-Carlo simulations are conducted and show that the 3D effect contributes a significant portion of the total bias, up to 10 km from clouds. Finally, radiative transfer simulations show that the contribution of instrument blurring is limited to the very close vicinity of cloud.

The paper provides, for the first time, a quantitative estimation of the relative contributions of cloud radiative 3D effect and instrument blurring to the total reflectance enhancement near clouds, using remote sensing observation tools. This

study's objectives are extremely important for the research of the transition zone between clouds and cloud-free atmosphere, which is essential for understanding the total radiative and climatic effect of clouds and aerosol.

Therefore, I recommend this paper for publication in *Atmospheric Chemistry and Physics*, with reservation to the authors' response to the comments below, in hope that my comments could help the authors to improve their paper.

Thank you for the thoughtful review and suggestions, which we found very helpful indeed.

**General comment**

According to the caption of Figure 1, the corresponding analyzed data are limited for low clouds (less than 700 hPa), above oceans.

1. I do not understand from the text itself whether the whole study is based on the specific subset of low clouds above oceans. If this is the case, please add this statement along the paper, including the abstract. This critical information will prevent misuse of this study's results in future research.

This is correct: the study is indeed based on low-level maritime clouds only. To point this out, we expanded a sentence in the abstract to "This study examines systematic changes in particle properties and radiation fields that influence satellite measurements of aerosols in the vicinity of low-level maritime clouds." Also, we expanded the first sentence of the introduction to "This study examines satellite measurements of aerosols near low-level

maritime clouds." Finally, we expanded the first sentence of the summary to "The purpose of this study is to better understand and measure aerosol properties near low-level maritime clouds."

2. In the same caption of Figure 1, it is also claimed that the limit of 700 hPa is equivalent to height limit of 3 km. When considering a global dataset between 60◦S to 60◦N, the altitude of 700 hPa may vary by hundreds of meters. Please clarify within the text what criteria used for selecting the data subset used for each and every section of this study, and provide an approximated mean altitude for the 700 hPa height, based on your data geo-location.

Because for brevity we removed Figure 1c as a non-essential component, we now discuss the definition of low clouds for MODIS data in Section 3, at the description of Figure 2. The text now says: "This figure and all subsequent figures use daytime data and the MODIS cloud mask that can detect clouds even outside the CALIOP track. Low clouds are defined as clouds with MODIS cloud top pressure greater than 700 hPa. While the altitude of the 700 hPa pressure level may vary by hundreds of meters, it tends to be near 3 km. (For single-layer clouds in our dataset, the mean CALIOP cloud top altitude at areas where MODIS indicates a cloud top pressure in the 690-710 hPa range is 2.98 km.)"

**Specific comments**

1. P. 32040 line 14, and along the paper: please keep consistent terminology. The term "*particle population*" may mislead, as it may be understood as aerosol only. Therefore I think it should be clearly mentioned along the paper, as it is in most cases now. I also suggest keeping consistency and use either "cloud droplets", "cloud particles" or simply "clouds". I prefer "cloud droplets" (although I'm aware to the face that some of the observed clouds may contain ice particle).

We added the clarification "including both aerosols and undetected cloud droplets" in Sections 1 and 4.

2. P. 32042 lines 22-23: it is mentioned that past studies found that high relative humidity is limited to the closest vicinity of clouds. How close? Please provide a quantitative distance scale, if possible.

To clarify this issue, we included the following sentence into the manuscript: "We note, however, that while Twohy et al. (2009) found modest humidity increases to extend more than 4 km away from clouds, their study as well as Bar-Or et al. (2012) found the areas of highest relative humidity (>90%) to be limited to less than a km away from clouds, with the sharpest increases occurring within a few hundred meters from clouds."

3. P. 32043 lines11-13: why was a 30◦ angle chosen for this section? It seems from Figure 5 that this angle is considered as the lower boundary of other parts of this study.

Presenting results for 30° solar zenith angle was an arbitrary choice. We note, however, that our initial tests of wavelength-dependence showed qualitatively similar behaviors for 30° and 50° solar zenith angles.

4. P. 32043 lines 19-20, and caption of Figure 2(b): I suggest replacing *(upper case 'x')* statements with the actual mathematical expression. It would take the same space and would be easier for the reader.

Following the suggestion, we added the mathematical expression to the text of Section 3. Although they make the paper slightly longer, we prefer keeping the upper indices c and f as they are also used in subsequent lines.

5. P. 32043 lines 22-24: it is assumed that R0.65 characterizes aerosol particle concentration. Please clarify whether it is size or number concentration, and refer to studies that support this assumption.

Because our argument is qualitative, we changed "aerosol particle concentration" to "aerosol loading"—which also matches the wording of the subsequent sentence. We felt that after this change we don't need to add a reference, as the sentence expresses the widely used principle that higher aerosol loading implies larger reflectance.

6. P. 32046 lines 14-16 and P. 32050 lines 2-5: I think that the conclusion that "*3-D radiative processes and instrument blurring are insignificant farther than about 10 km from clouds*" is pretty important, and should be mentioned again in the summary section, as it provides an effective distance scale for considering these factors.

We included this point into the summary, so the relevant part is now "Finally, theoretical simulations for the analyzed yearlong dataset indicate that neither instrument effects nor 3D radiative processes contribute significantly to the enhancements observed farther than 10 km from clouds. Within 10 km from clouds—where the majority of clear sky areas occur—the simulations indicate that while instrument effects are fairly modest, 3D radiative processes contribute significantly to the observed enhancements."

7. P. 32048 lines 5-6: why has the reference observation been chosen to be 20 km from the nearest cloud? Does this specific distance have some physical reason?

We chose 20 km as our reference distance for consistency with our earlier papers that also used 20 km (Várnai and Marshak 2009, 2011, 2012). Lacking a clear-cut choice due to the gradual fading away of near-cloud changes, 20 km appears suitable because using a 20 km cut-off captures most of the near-cloud changes—although the results in Koren et al. (2007) show that the gradually weakening changes continue even beyond 20 km.

8. P. 32049 lines 20-22: I recall several past studies showing similar exponential functions for radiative properties near clouds (e.g. *Koren et al.*, 2007, already cited in this paper), these may support the selection of exponential function or even the shown fits.

We included into the paper the sentence "We mention that exponential behavior near clouds was noted in earlier studies (e.g., Tackett and Di Girolamo 2009)."

Koren et al. (2007) used a logarithmic fit, which also fits well the enhancement as a function of distance to clouds.

9. P. 32049 lines 21-24, and P. 32050 lines 10-13: if there are still "*not-yet-considered 3-D effects*", I would like, as a reader, to get more information about them. Why were they not-yet-considered? How can we know they are 3-D effects?

We clarified this by expanding the sentence so it now includes "…not-yet-considered 3D effects (as discussed at Figure 5a, these involve surface reflection, aerosols, and partly cloudy pixels)…". As mentioned in the discussion of Figure 5a, we plan to include these effects in future simulations; we just need to improve/expand our Monte Carlo model first.

10. Figure 5(a): I am curious to know if you can explain the abnormal behavior of the Monte Carlo (green curve) around distance of 5 km.

Our guess is that the results at 5 km are a bit too high because of simulation uncertainties, which include sampling uncertainties (i.e., clouds being thicker around pixels for $d$=5 km) and uncertainties in the Monte Carlo radiative simulation itself.

**Technical corrections**

1. All figures: please make sure that the fonts are large enough for easy reading, even when printed (extreme example – Figure 6).

We increased the size of axis titles and/or labels in Figures 1a,b, 2b,c, 4, 6a,b,c.

2. Figure 2(a): since this is only a theoretical demonstration, and the Y axis has no units, I suggest rescaling the Y axis to the values of the lines in the plot.

We didn't quite understand this suggestion and so we didn't change the Y axis of the plot.

3. Figure 2(a): I suspect that the X axis is linearly scaled, despite the label.

Good eye! We shifted the dashed line indicating 0.55 μm slightly to the right, so now the distance between the 0.65 and 0.55 μm lines is 1.06 times larger than the distance between the 0.55 and 0.47 μm lines. This is appropriate as

$$( (\log 0.65 - \log 0.55) / (\log 0.55 - \log 0.47) ) = 1.06.$$

4. Figures 2(b) and 2(c) captions: please include within the caption text the definitions for: "far", "close", "R0.47", and "R0.55". Please rephrase the caption for panel 2(c) accordingly.

We added the following sentences to the caption of Figure 2c: "The close and far categories include areas that are less than or more than 5 km away from the nearest cloud, respectively. $R_{0.47}$, $R_{0.55}$ , and $R_{0.65}$ are the mean reflectances observed by MODIS at 0.47, 0.55, and 0.65 μm wavelengths."

5. Figure 3(b) caption: please include within the caption text the definitions for: "near-cloud", and "relative" (far to near-cloud?).

We added the following sentences to the caption of Figure 3b: "These relative enhancements (*RE*) are obtained using $RE = (X_{d>5\text{km}} - X_{d\leq 5\text{km}}) / X_{d\leq 5\text{km}}$, where $X$ is the particle contribution to either 532 nm CALIOP backscatter ($b^p$) or 0.55 μm MODIS reflectance ($R^p$), and $d$ is distance to the nearest cloud below the altitude of the 700 hPa pressure level (~3 km)."

6. Figure 4 caption: please include within the caption text the definitions for: "near-cloud", and "relative" (relative to 20 km?).

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

7. Captions of Figure 5(a), Figure 6(a) and Figure 6(b): please mention in the caption that the enhancement is relative to the reflectance measured 20 km from clouds.

We included the following sentences into the captions for Figures 5 and 6, respectively:

"Enhancements are defined as the difference from the mean value observed 20 km away from clouds."

"The increase is defined as the difference from the median value observed 20 km away from clouds."

**References**

Koren, I., Remer, L. A., Kaufman, Y. J., Rudich, Y., and Martins, J. V.: On the twilight zone between clouds and aerosols, *Geophys. Res. Lett.*, **34**, L08805, doi:10.1029/2007GL029253, 2007.