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Atmospheric Chemistry and Physics Discussions

# *Interactive comment on* "Unveiling aerosol-cloud interactions Part 1: Cloud contamination in satellite products enhances the aerosol indirect forcing estimate" *by* Matthew W. Christensen et al.

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Responses to reviews of the original submission

Review Comments in black; responses in blue

**Anonymous Referee #2** The paper addresses a very important question, whether using satellite data obtained right near clouds may bias satellite estimates of indirect aerosol radiative forcing. This may occur if complications (such as the presence of cloud drops in supposedly clear areas, aerosol swelling, cloud shadows, or enhanced scattering from clouds into aerosol fields) made aerosol observations near clouds un-



reliable or unrepresentative. The paper presents a new approach, which avoids these dangers by excluding the potentially compromised aerosol data that was obtained right near clouds. The authors then find that this approach greatly reduces the estimated indirect aerosol radiative forcing values. The overall approach seems reasonable, but I have some significant concerns. The two most important ones are (1) whether random sampling uncertainties have a large influence on the conclusions, and (2) whether the proposed method yields weaker aerosol-cloud relationships because it uses aerosol data obtained farther away from clouds, where the aerosol population may be less representative of the aerosol population that enters the clouds. Because of these and other concerns, I recommend major revisions to the manuscript.

» Thank you for the great feedback, particularly, the main points regarding the statistical sampling. Further analysis of the spatial distribution of the aerosol field was carried out based on your comments. This analysis has increased our confidence that these results are not merely a statistical anomaly.

Most important comments

Page 8, Lines 20-21: It would be important to discuss whether the relationship between cloud and aerosol properties (and so the estimated indirect aerosol radiative forcing values) may be weaker for aerosols farther than 15 km (that is, for CAPA-L2_15km) simply because aerosols farther away are more likely to be in a different air mass (and therefore are not representative of the aerosols that actually interact with the clouds). I am concerned about this, because Line 8 of Page 7 mentions that the median distance between the cloud and aerosol pixels paired up by CAPA-L2_15km is 27 km, which implies even larger distances in some cases.

» This is a valid concern. We have implicitly assumed in this study that the aerosols are fairly homogenous across large spatial scales, up to 150 km according to the results presented in Anderson et al. (2003). However, to corroborate this claim additional tests have been carried out to address the spatial scale dependence of the distance between the aerosol and cloud data. Using the observations from AATSR we run an additional test in which the aerosol is removed from nearby clouds up to a distance of 30 km and then each cloud is paired to the nearest far-field aerosol pixel at this scale. Overall, the aerosol indirect forcing estimate is somewhat smaller in strength using 30-km scaling ($-0.20 \pm 0.26$ W/m$^2$) compared to the scaling at 15 km ($-0.28 \pm 0.27$ W/m$^2$) but thee differences between the composites are insignificant. This implies that the far-cloud aerosol statistics are representative of the same airmass as those found closer to clouds. This paragraph added to the manuscript.

» Furthermore, we have examined the spatial autocorrelation length scale using a continuous assimilated reanalysis aerosol product, the CAMS model at 0.125 degrees (because it was already available on our system), and find in this dataset the aerosol has a typical spatial autocorrelation length scale of greater than 150 km over 10x10 degree regions in most locations (see Figure 1 in this response below) which is in general agreement with the data presented in Anderson et al. (2003). Therefore, we are confident that in most cases the aerosols located within 15 km of a cloud are highly likely to be in the same airmass as those located farther away up to 150 km in most locations.

Figure 7: The large and overlapping error bars raise some questions about the statistical reliability of results. Could it be that the results from CAPA-L2_15km are smaller than the results from the other methods only because of random statistical fluctuations? The similarity of MODIS and AATSR results, and the similar tendencies in Figs. 8 & 9 suggest that the qualitative behavior in Figure 7 is correct despite the large error bars, but it would be important to address the issue of statistical reliability.

» An argument could be made that the similarity of MODIS and AATSR results suggest that the tendencies are in fact correct despite the relatively large error bars. This is probably likely for two reasons: 1) the standard deviation of the spatial distributions of Figures 4 and Figure 8 would indicate that the spatial maps are quite smooth. It is not the case that in some grid point's there are larger values and in some grid points



smaller values, as one would expect from random fluctuations. In addition, the forcing estimate computed using CAPA-L2_15km (far-field aerosol pairing) decreases for each grid point compared to CAPA-L2 (near-cloud aerosol pairing) and not just in the average. Finally, the decrease for MODIS (with less than 1/4 as many data points) and AATSR is similar which indicate that the results are robust and not random despite the large error bars.

Other comments Page 5, Lines 6-7: Should clarify the definition of c_m_overbar, which is now: "cm is the climatology of low-level clouds having cloud top pressure greater than 500 hPa and composed of liquid phase droplets over ocean regions" to show that the climatology is the climatological mean of ***cloud cover fraction*** of liquid water clouds with top pressures exceeding 500 hPa over ocean. Also, it seems best to delete "low-level" from the sentence, as 500 hPa serves as the definition for low levels, and the current wording could be misunderstood as c_m_overbar telling what fraction of low-level clouds occur below the 500 hPa level (which would imply a remaining fraction of low-level clouds that occurs above the 500 hPa level).

» I agree, the way it is currently written is confusing. "low-level" in this context is redundant anyway so it was removed.

Page 5, Line 10: the first term represents changes not in cloud albedo alone, but in the difference between cloud and clear sky albedos (with clear sky albedo also changing with aerosol loading). So perhaps the word "represents" could be replaced by something like "includes". Or, perhaps even better, the text could specify that the first term represents the fact that aerosol loading (AI) has different impacts on the albedos of cloudy and clear columns. (If it had the same impact on both columns, this term would vanish.)

» The clear-sky albedo change with AI (i.e. $dA_{clr}/d\ln AI$) is small but included in this equation for completeness. It is generally an order of magnitude smaller than the cloudy-sky albedo change with AI so $dA_{cld}/d\ln AI$ essentially represents the strength of the intrinsic aerosol radiative forcing but this is a good point and have therefore changed this word from "represents" to "includes."

Page 5, Line 15: At the end of the line, what does F_anth represent and where does it come from? (In other words, how does F_anth relate to tau_anth?)

» F_anth is explicitly derived from the MACC-II reanalysis model. This is now stated prominently in the manuscript and included in the syntax for the anthropogenic aerosol fraction equation.

Page 6, first paragraph: While it is clear why the adopted hybrid approach is faster than the brute force approach (used for high cloud fractions), it would help to also discuss why the hybrid approach is faster than always using the low-cloud-fraction approach.

» In general, if the cloud fraction is high but we were to use the low-cloud fraction looping method the algorithm will run slower. This is because there is a higher likelihood of an aerosol pixel located farther away from the cloud (when the cloud fraction is high), and in this case, the algorithm will require more looping around adjacent pixels until a clear-sky pixel is found, therefore the brute force method for this condition. This point has been clarified in the text

Page 6: It would help to clarify somewhere, what happens when there are two or more aerosol pixels that are at the same distance from a certain cloud: Does CAPA use only one of these pixels, or does it average the aerosol properties over all of these pixels?

» Good point to include here! We have added: "if two (or more) aerosol pixels are located at the same distance from the cloud observation then one of them is selected at random."

Page 7, line 6: In order to clarify that clouds are paired with aerosols and not with other clouds, I suggest changing "clouds are paired based on the nearest located aerosol (CAPA-L2) and based on the nearest aerosol? to something like "clouds are paired with the nearest located aerosol (CAPA-L2) and with the nearest aerosol. . ."



» Thanks for noticing this grammatical mistake we have modified the sentence based on your suggestion.

Page 7, Line 18: I suggest either clarifying what "1-sigma regression estimate" refers to, or deleting "1-sigma". The same applies to Page 9, Line 11.

» The "1-sigma regression estimate" refers to the "standard error" of the regression coefficient. This has been added to the text and is now referred to as the "1-sigma standard error regression estimate." This is a standard measurement of the error and describes the accuracy of the linear least squares fit. The uncertainty on the radiative forcing estimate is computed by averaging the 1-sigma standard error regression values over all of the global grid-boxes.

Page 8, Line 13: The word "stronger" should be changed to "steeper", which is a more suitable word for describing slopes.» Done

Page 8, Line 24: "MODIS afternoon-train" should be changed to "MODIS Aqua".

» Correct, the comparison uses MODIS on Aqua and also included the CERES broadband flux data so I have changed this to: "MODIS Aqua and CERES".

Page 18: "CAPA-L2_15km; blue" should be changed to "CAPA-L2_15km; green".

» Nice catch, done.

Page 8, Line 31: I suggest replacing "shown in Figure 9" by "shown in Figures 8 and 9"; otherwise the order of the two figures should be reversed (so that Figure 8 is referenced before Figure 9).

» Done

Page 9, Lines 8-9: In the sentence "we have reconstructed the pre-averaged aerosol product at first through the removal of near-cloud aerosols in the standard AATSR and MODIS data", it would be important to clarify what is meant by "removal of near-cloud aerosols": Does this mean removing aerosol data for 10X10 km areas that have clouds within 15 km? If so, how was this removal implemented: Was a 10X10 km area removed if any part of it was within 15 km from the nearest cloud? My guess would be that 1 km pixels within 15 km to the nearest cloud were eliminated first, and then the remaining pixels were processed by the 10 km-resolution algorithm.

» The screening approach is very conservative, that is, 10x10 km areas are removed if "any part" of it was within 15 km from the nearest cloud. This important point has been included in the text.

Page 9, Line 19-20: Does Table 2 show results for all oceans, or does it exclude polar regions or covered by sea ice?

» Geographical range was added to the caption ($60°S - 60°N$). Satellite retrievals are not used if they are over land or sea ice covered regions has also been added to the methodology section for clarity.

Page 21: Table 2 (along with the lack of CAPA in Figs. 8 & 9) points to an inherent limitation of CAPA: It cannot be used to estimate the extrinsic (or overall) forcing, only the intrinsic forcing. This important limitation of CAPA should be mentioned somewhere prominently, and probably even in the summary or abstract.

» Yes, it is true that the output from CAPA itself precludes our ability to compute the extrinsic forcing at the pixel scale. Running CAPA on pixel-scale data is also impractical for most users of this data due to the large data volume required. We have therefore included these points into the summary section but also remind the reader again that CAPA forms an important step in correcting these L3 type products.

Page 10: The text of Section 8 seems to be missing.

» Code to process aerosol, cloud, and broadband fluxes using ORAC can be obtained via https://github.com/ORAC_CC/ORAC.

Page 10, first line of Section 9: A typo: ATSR should probably be changed to AATSR.



» Nice catch. This was changed accordingly.

## References

Anderson, T. L., Charlson, R. J., Winker, D. M., Ogren, J. A., and Holmen, K.: Mesoscale Variations of Tropospheric Aerosols, J. Atmos. Sci., 60, 119–136, doi:10.1175/1520-0469(2003)060$<$0119:MVOTA$>$2.0.CO;2, 2003.

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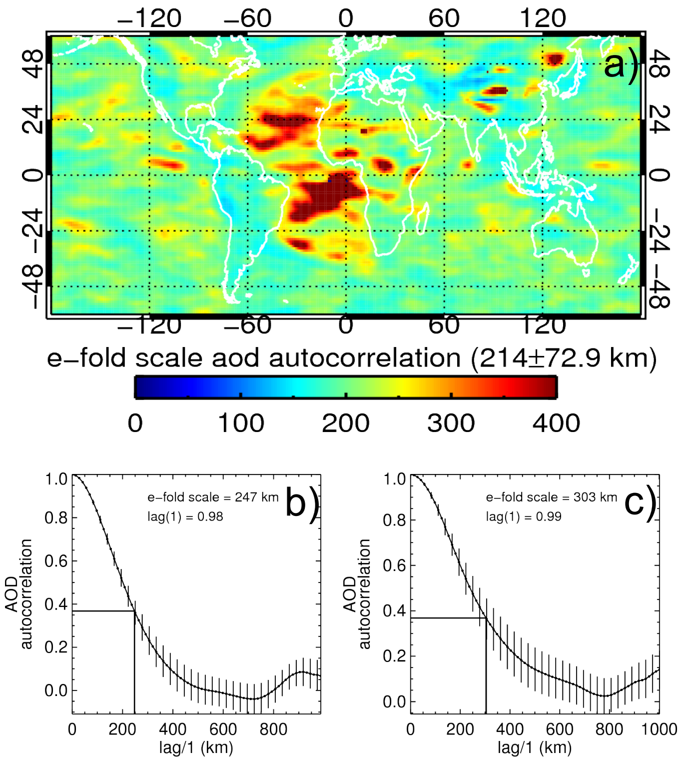


**Fig. 1.** a) 1/e folding AOD autocorrelation length scale determined using CAMS reanalysis data in 10x10 degree regions. lags plotted b) off the california and c) S. Africa Coasts.