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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 #3**

This paper examines how colocation and sampling choices made in aerosol cloud interaction studies impact the strength any aerosol cloud relationships derived in those studies. Using data from MODIS and AATSR, the authors use a nearest neighbour approach to select pairs of aerosol and cloud pixels for analysis. They show that using



aerosol retrievals located more than 15km from a cloud reduces the implied aerosol forcing from the AI-cloud albedo relationship as well as the implied extrinsic forcing due to a reduced AI-cloud fraction sensitivity.

The paper is well written and makes an important point about the sampling of aerosol retrievals when used in aerosol-cloud interaction studies. Previous work has shown that aerosol retrievals are enhanced near clouds, but this work goes further, estimating the impact of this effect on the implied radiative forcing. There are a few points and one algorithmic suggestion that I would make, but other than that it is suitable for publication in Atmospheric Chemistry and Physics.

» Thank you for the thoughtful and careful review of this manuscript. These are great suggestions and have led to further testing, specifically on relating the intrinsic/extrinsic forcing concepts to other methods which use CDNC relationships.

Main points

I appreciate that the intrinsic forcing concept has been used in the past, but I am not clear that the results from this necessarily carry across to other studies using an aerosol-CDNC relationship to constrain the aerosol indirect forcing. The intrinsic forcing relies on all the properties of the cloud being uncorrelated to CF. However, Feingold et al. (2016) showed that the cloud albedo can be very strongly correlated to CF. Given that cloud properties that are correlated to the CF have the potential to generate spurious aerosol-cloud relationships (Gryspeerdt et al., 2014), this might affect the evaluation of the intrinsic forcing.

» The intrinsic forcing estimate is based on aerosol-cloud susceptibilities where the cloud cover fraction is 100% so there will be no dependence on CF unless the cloud mask is wrong (indicating a cloud where otherwise would cloud-free due to a satellite retrieval failure, but this is unlikely over ocean regions where the surface is "dark"), which for regions over the ocean this is not likely to be a very large concern.

It is not clear how strongly aerosol-CDNC relationships are affected by covariation with CF, so it would be very interesting to see how the aerosol-CDNC type forcing calculation (e.g. Quaas et al., 2008) is affected by near-cloud aerosol retrievals in addition to the results presented here. I think that this would be necessary if the authors are to apply their conclusions to all satellite-based estimates, rather than just those that are based on the intrinsic forcing concept.

» This is an excellent point. And we agree that extending this analysis to more approaches is essential before applying these conclusions to "all" satellite-based estimates. Therefore, we have included additional diagnostics in the output from CAPA and forcings have been computed using the prominent aerosol-CDNC type approach used in Quaas et al. (2008). In this comparison, we focus on the "cloud albedo effect" which is computed using equation (10) of Quaas et al. (2008). The primary difference between this approach and the "intrinsic forcing" equation used here is the product of dlnNd/ dlnAI with the planetary albedo sensitivity term. Using the same initial inputs for liquid cloud fraction, liquid cloud albedo, solar insolation, and anthropogenic aerosol fraction we find the cloud albedo effect from Quaas et al. (2008) provides a somewhat smaller forcing estimate compared to the intrinsic aerosol indirect forcing method the impact of near-cloud aerosols still results in a larger aerosol indirect radiative forcing estimate. For example, the PRE_AVG ($-0.36 \pm 0.32$ W/m$^2$) and CAPA-L2 ($-0.38 \pm 0.22$ W/m$^2$) composites are significantly larger than the PRE_AVG_Corr. ($-0.09 \pm 0.28$ W/m$^2$) and CAPA-L2_15km ($-0.17 \pm 0.19$ W/m$^2$) composites. In conclusion, both methods provide support that the aerosols located near clouds enhance the aerosol-cloud radiative effect compared to the selection of aerosols that are located farther away from clouds. This can be understood from the sensitivity of CDNC to a relative change in AI given by dlnNd/ dlnAI. Figure 1 below shows the global distributions of the CDNC sensitivity for each regime with smaller values associated with the aerosols located farther from clouds.

When calculating the radiative forcing, the authors use an anthropogenic aerosol frac-



tion from Bellouin et al. (2013). This fraction is derived from AOD, not AI, and so may be smaller than expected in some regions, especially where dust dominates. There are other possible anthropogenic aerosol products (such as a fraction from the AeroCom models, Ghan et al. (2016)), but it should be noted that this method might produce an underestimate in the forcing through a too small anthropogenic fraction.

» In this calculation we have assumed that the fractional change in the anthropogenic AOD is equivalent to the fractional change in anthropogenic AI. As you note, this assumption may lead to an underestimation of the aerosol indirect forcing. We have clarified this point in the text and state this assumption prominently. The current MACC product that we use here http://apps.ecmwf.int/datasets/data/cams-climate-forcings/ does not contain an estimate of the anthropogenic aerosol fraction based on the AI calculation. As I understand, later versions of this product will provide the AI-based changes. Our companion paper Neubauer et al (2017), ACP examines this in more detail examining the differences related to the use of changes in AOD VS AI datasets.

While the authors have already produced this dataset, if they wanted to re-run their analysis (or for others who want to reproduce it), it is worth noting that there are much more efficient algorithms for finding nearest neighbours in a large dataset. Binary search trees, such as a k-d tree or VP tree would work well here. A quick test using the standard python/scipy cKDTree on a close-to-worst-case MODIS granule (MYD06_L2-2013-136-2315, about 40% cloud fraction), found nearest neighbour aerosol pixels for all the cloud pixels (about 1million) in about 1 second with no restrictions on distance. Obviously the algorithm used by the authors can provide extra information, but this might be useful for further work.

» We agree there are more advanced and efficient methods to compute nearest neighbour pixels from satellite data using KdTree's, ect. These suggestions are excellent and would highly encourage the use them to others. However, it is beyond the scope of this work to implement these changes now and so have included this information in the summary for others who might like to reproduce the results using these advanced

methods.

Minor points P2L22: Is it clear that there is a co-location 'problem'? The benefit of CAPA selecting the closest aerosol-cloud pairs is not mentioned beyond increasing the number of samples.

» Fundamentally, we want to know about the aerosol within a cloud. We can't obtain this information from these passive sensing instruments, so we have to use measurements somewhere else and give a reasonable argument why they are representative. Our main points are that (a) aerosols near cloud are affected by contamination/humidity/3D-effects and therefore aren't representative, (b) we assume aerosol vary slowly in space, so (c) we think the closest aerosol is a good proxy. The coupling between aerosol and cloud could potentially be improved using a back-trajectory model as was used in Bréon et al. (2002) but this needs to be explored further. We have included this subsequent approach in the paper because we think it could be relevant to future work.

P2L34: How are the aerosols assimilated into models affected by wet deposition (compared to the aerosols retrieved by satellite)? Perhaps this should refer to 'aerosols from reanalysis products'?

» Good point. The impact of wet deposition in the reanalysis model is unconstrained in cloudy areas where the satellite cannot retrieve aerosol. This point has been clarified in the text.

P3L6: Does this really provide improved statistics? Many of the retrievals are strongly correlated in space (and time), so it is not clear that more individual datapoints provides more information.

» The answer depends on the scale of the interaction. At the local-scale (1 km) the AOD retrievals are completely independent from each other but examining the relationship between AOD over some distance we expect spatial autocorrelation. Here, we are essentially measuring AOD several thousand times and so hammering down the



random uncertainty at the local scale. However, as you mention there could be correlation in space (and time). This will depend on the cloud and aerosol type. For some cloud/aerosol types there could be strong correlation but for others maybe not. I would argue that this approach provides potentially more information since it can decrease random uncertainty. However, for (large) correlated cloud/aerosol fields it will probably not provide very much additional information on sampling (see comment P7L19 below). In the response to your next comment (P7L19) we provide an estimate based on a preliminary examination of the autocorrelation spatial scale and determine that the number of samples is not substantially increased over larger spatial scales. As this is an important point we have added in the manuscript that "the number of AOD retrievals are increased but the number of degrees of freedom are likely not significantly increased due to the relatively large spatial autocorrelation length scale of the aerosol optical depth (e.g. Anderson et al. (2003), Schutgens et al. (2016), Kovacs (2006); Santese et al. (2007); Shinozuka and Redemann (2011))."

P5L30: Some studies (e.g. Koren et al. 2012) perform interpolation between 1 by 1 degree gridboxes, which is a larger effective scale than the 150km shown here. I don?t imagine that limiting the pairs to 150km is much of an issue, but it is not obviously correct to ignore them.

» In general, we would not expect the aerosol at lengths greater than 150 km to be very representative of the same airmass as the location of the cloud. As shown in the following papers (e.g. Anderson et al. (2003), Schutgens et al. (2016), Kovacs (2006); Santese et al. (2007); Shinozuka and Redemann (2011)) and our preliminary analysis of CAMS data reported to reviewer #1 comments the typical length-scale of the aerosol field can vary significantly based on location. Note, this length-scale might be longer than that obtained using the raw satellite observations since the analysis is based on the smoothly varying 0.125 degree CAMS reanalysis data. In general, it may be suitable to construct aerosol-cloud pairs that have larger distances than 150 km in some regions (e.g. off the West coast of Africa) but in other regions (Central

Pacific) this would not be a suitable choice as the length scales can be much shorter. A 150 km length-scale seems to be a reasonable threshold based on these spatial autocorrelation studies. Therefore, we would not expect to see a significant benefit in sampling by extending this range to larger than 150 km as most of the aerosol-cloud pairs are established in most regions within the first 50 km.

P6L10: Does this interpolation then mean that there are some 10km pixels which are considered both valid and invalid when filtering for pixels 15km from a cloud?

» 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.

P7L19: As mentioned above, the number of degrees of freedom is smaller than the total number of cloud-aerosol pairs. How is the error estimate then calculated (does it account for the autocorrelation in the cloud and aerosol fields)?

» The uncertainty estimate of the effective radiative forcing is determined by globally averaging all of the 1-sigma error estimates from each region. The 1-sigma standard error estimate in each region is computed from the least squares fit regression coefficient which is affected by the number of degrees of freedom. This can be shown in the following equation

$$\sigma = \sqrt{((SS_y/SS_x) - b^2)/(n^* - 2)} \quad (1)$$

where, $SS_y$ and $SS_x$ is the ratio of the covariance matrices, and b is the y intercept of the fit-line and $n^*$ is the number of samples measured by the degrees of freedom. As shown by this simple equation n only appears in the denominator of the square root. Therefore, the error estimate becomes larger by $\sqrt{1/n}$ as the number of samples decreases. We have not included the impact of spatial autocorrelation of aerosol and cloud fields in this study but we do expect the strong spatial autocorrelation between aerosol retrievals. This is expected to decrease the number of degrees of freedom.



Although, the ratio of the decrease in DOF would be similar across all of composites based on the formula in Bretherton et al. (1999)

$$n^* = n(1 - r(\Delta t)^2)/(1 + r(\Delta t)^2) \quad (2)$$

where, $r\Delta t$ is the one-lag autocorrelation of the time-series (or spatial direction from origin) with itself, larger values of the autocorrelation decreases $n^*$.

P8L25: 0.1Wm-2 out of 0.4Wm-2 is still quite a large discrepancy

» True, but the 0.1 W/m2 value is about half the size of the 1-sigma standard error on the regression. So we argue that it is within the noise level which is 0.2 W/m2.

P10L23: The apostrophe in NERCs is not rendering correctly » DONE

Fig. 9: These extrinsic forcings (for the corrected L3 data) are quite close to those proposed by Gryspeerdt et al. (2016), which could provide supporting evidence for this proposed extrinsic forcing.

» This key reference has been included in the text.

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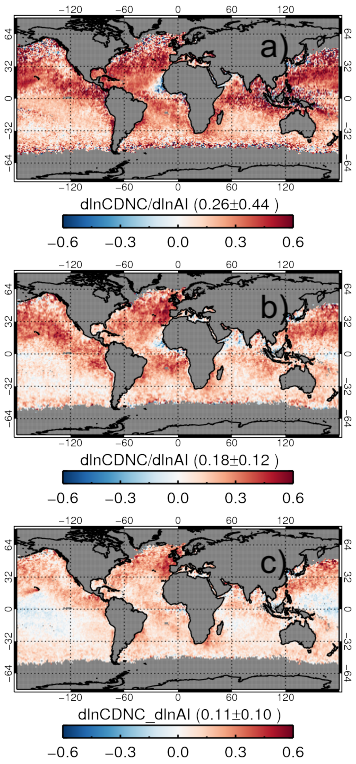


**Fig. 1.** Log change in droplet number concentration to a relative change in aerosol index for a) pre-averaged, b) CAPA near-cloud aerosol, and c) CAPA_15 km far-field aerosol using 2002-2012 AATSR ORAC.