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Interactive Comment

# *Interactive comment on* "Links between satellite retrieved aerosol and precipitation" *by* E. Gryspeerdt et al.

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*This manuscript explores correlations between satellite-derived aerosol and precipitation information in the context of cloud regimes. Two novel methodologies are employed that seek to (a) separate the effects of correlations between cloud fraction and aerosol concentration (inferred from AI) and (b) better expose the time-dependent nature of aerosol-cloud interactions. The investigation of lag-correlations between AI and precipitation, in particular, leads to interesting new evidence for both aerosol invigoration and scavenging processes. The paper is generally well-written and the subject is very appropriate for ACP but there are some methodological issues that warrant additional discussion and some important omissions from the overview of the latest*



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Interactive Discussion

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*literature on the subject. I would suggest some revisions to the manuscript to address these issues. Specifically:*

*1. A minor point but the title should probably reflect the fact that the focus is primarily on 'tropical precipitation'*

Thank you for this comment. We had originally used "tropical" within the main body of this work, but have been reminded by the editor that our study area is not strictly limited to the tropics. On balance, we prefer to leave the title as it is.

*2. The authors provide a good overview of some of the concerns associated with past efforts to explore aerosol indirect effects using primarily satellite observations but they make very little reference to recent literature that provides supporting evidence for such effects (on warm rain systems in particular) using independent methods based on satellite-borne active sensors. Specifically, satellite radars provide a more direct measure of the existence of precipitation, raindrop size distributions, and vertical structure (e.g. precipitation top) at a resolution that is much more representative of individual precipitation elements than passive sensors. Differences in rainfall estimates from the TRMM Microwave Imager (TMI) and Precipitation Radar (PR) and their implications for precipitation susceptibility to aerosol concentration in the East China Sea were pointed out by Berg et al. (2006, 2008). Since then, many of the aerosol effects on warm cloud and precipitation microphysics, cloud vertical extent, and the occurrence of precipitation noted on page 6824 have been documented (e.g. Lebsock et al, 2009 and L'Ecuyer et al., 2009). Both of these studies make use of the fact that cloud radar is the only instrument in orbit that provides a direct measure precipitation occurrence and a direct measure of the vertical extent of the precipitation column in individual storm systems. These studies also make an effort to reduce both types of meteorological covariation errors mentioned in the paper by (a) looking at multiple sources of aerosol information (AOD, AI, and transport models); (b) focusing on individual cloud elements as opposed to larger grid boxes that may be susceptible to CF-AOD relationships; and (c) stratifying results by atmospheric stability and cloud regime (via liquid water path) to address the*



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*issue of regime and cast results in terms of precipitation efficiency. I believe it is important to mention these studies as alternative corroborating evidence for aerosol impacts on precipitation and cloud structure as the observations and methodologies differ dramatically from the more common methods of regressing average cloud and aerosol properties from passive sensors over coarse grids. This is not to say that these studies don't suffer from their own sources of uncertainty but the independent methodologies employed lends support to the fact that aerosols exert an influence on the character of warm rain systems that appears somewhat at odds with the conclusions of this study (but there is reason to believe this may be due to shortcomings in the rainfall dataset employed here).*

As pointed out by the reviewer, our study is not capable of investigating possible aerosol suppression of precipitation. The time-resolved nature of this study either requires multiple satellites with different overpass times (as in Gryspeerdt et al. (2014)) or the use of non-sunsynchronous instruments (as in this study). Unfortunately CloudSat cloud profiling radar is flown on only one sunsynchronous satellite, preventing its use in this study (useful as it would be).

The CloudSat orbit prevents use from investigating the influence of aerosol on light precipitation, we have concentrated on the possible aerosol invigoration of convective clouds. As this mainly involves heavier precipitation, the TRMM precipitation radar and microwave imager are appropriate for the retrieval of precipitation from the clouds under study.

However, we agree that the manuscript was not clear on this point, so we have expanded sections in the methods, discussion and conclusion to better explain the rationale for the use of the TRMM instruments and why precipitation suppression effects would not be expected in this study.

This explains why there is very little change in precipitation from the marine stratocumulus regime, as the precipitation observed from this regime may be more closely related to cloud water rather than precipitation. This is touched upon in section 3.3, but we have now expanded upon it in section 4.1.

*3. While I like the novel nature of the methodology there are some aspects, primarily related to the choice of datasets used, that have an impact on the interpretation of the results. Several modifications to the statements in Section 3 and the overall conclusions of the manuscript are necessary to reflect these issues.*

*a. If I understand correctly, all analysis use variables averaged to 1° spatial resolution but it is unclear how this coarse resolution translates to analyzing actual cloud and precipitation processes. While this is reasonable for more homogeneous quantities like aerosols, 1° averaged cloud top temperature (CTT), cloud optical thickness, and especially rainfall rate seem to be rather abstract quantities given typical spatial scales of clouds and precipitation. Cloud and precipitation processes do not occur on scales of 100's of km but rather on the scales of individual cloud systems so it is not completely clear that the analysis really addresses cloud-aerosol interactions at the process level. Given that each grid box may contain a diverse distribution of clouds, it is not entirely clear how unique the regimes classified based on mean cloud top pressure, cloud top temperature, and cloud optical thickness over a 12,000 km$^2$ area really are. There could be a variety of clouds at different stages in their lifecycles within the same grid box yet this appears to be neglected in the following discussion of diurnal cycles and the separation of warm vs. mixed-phase clouds. A mean CTT warmer than 0°C, for example, does not ensure that mixed-phase processes aren't occurring somewhere within the grid box. Also, it is unclear what fraction of the clouds within the domain may actually interact with the aerosols present at any given time. The authors mention the perils of using composites of satellite snapshots but it is not clear that such an approach is any worse than analyzing the mean properties of large ensembles of clouds.*

We agree that this is a large region over which to study aerosols and precipitation. The main reason for choosing to use a large region is to investigate the behaviour of a field of clouds, rather than a single cloud, as the properties of fields may be different.



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The quasi-equilibrium theory (Arakawa and Schubert, 1974) suggests that a field of convective clouds is primarily controlled by the large scale environment. An influence of aerosols on precipitation from a field of clouds rather than on the clouds individually is therefore particularly interesting, as we account for variations in the large scale environment in our study.

While there may be many different clouds at different stages of development within a single 1° gridbox, the average development of the field of clouds as part of the diurnal cycle allows the observation of a possible aerosol influence on precipitation from convective clouds.

Although the regimes are defined over a large region, they are largely made up of clouds with similar properties (Williams and Webb, 2009; Gryspeerdt and Stier, 2012). While the splitting of clouds by regime is useful when accounting for the influence of meteorological variation, the exact separation of the regimes is not vital to the results (early versions of this study used the regimes from Williams and Webb (2009) and showed similar results). The similarity of the response of the regimes may indicate that they are not separated in the ideal manner, although determining the best way to separate clouds into regimes for a study of aerosol-precipitation interactions is beyond the scope of this work.

*b. There are also concerns regarding the precipitation dataset used. Few rain events in the tropics cover a full 1° grid box so it should be noted that the results must be interpreted as changes in the distribution of rainfall (i.e. the PDF) within the grid box, once again limiting the ability to attribute changes to specific processes. More importantly, the 3B42 rainfall has some characteristics that severely limit its utility for this application mostly tracing to its heavy dependence on passive microwave (PMW) and infrared observations. While this is noted in the paper, the full extent of the possible impacts on the results are not discussed. Two major issues immediately come to mind. First, both the microwave and infrared are known to underestimate rain from isolated warm rain systems due to (a) the large field of view of passive microwave instruments and (b) the*



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*lack of cold cloud tops to trigger rainfall detection in the infrared. Second, while more sophisticated physical algorithms are being developed, current passive microwave algorithms over land are based on simple regressions between surface rainfall and ice scattering in the highest frequency channels. These algorithms are tuned to give appropriate monthly mean rainfall statistics but it is doubtful that they capture shorter-term fluctuations associated with aerosols. Like Berg et al. (2006) there is validity to the pointing out that the PMW/IR statistics appear to be modulated by aerosols but the results should be better connected to the physical signatures that govern rainfall detection/retrieval in the algorithm, especially noting the contrast in physics between the land/ocean-based retrievals and sensitivity to warm/cold rain processes (i.e. emission vs. scattering, role of drop size distribution, role of spatial scales, etc.). This is more than just a matter of semantics, it has significant implications for the interpretation of the diurnal cycle results, land/ocean contrasts, and, especially, the finding that warm clouds exhibit less sensitivity to aerosol than colder clouds. It seems very plausible that this difference in warm vs. cold rain, especially, could simply be an artifact of the fact that the precipitation dataset used has greater sensitivity to cold-rain processes than warm rain processes. The shallow rainfall results over land are particularly suspicious and may be related to the preceding comment that a 1○ mean CTT warmer than 0°C does not adequately screen liquid phase precipitation.*

It is difficult to completely account for the issues in the precipitation retrieval. To try and deal with this, we have included multiple different satellite products that are connected with precipitation (3B42 microwave, TRMM radar profiles and TRMM LIS). As the radar results in the SI show similar results to those seen in the 3B42 product, this would suggest that the results are not entirely due to issues specific to the passive microwave instruments. The observation of wet scavenging at times before T+0 also indicates that the changes in precipitation are actually due to a change in surface precipitation, as they could not be caused by a change in cloud properties (eg. a change in scattering from cloud anvils). We don't believe that issues in the retrieval associated with the IR component are important, as when the study is repeated without using the

IR component, similar results are obtained - these results are included in the SI.

However, we have expanded on possible precipitation retrieval errors in section 4.1, especially with regard to changing droplet size distributions. We have also noted that the lack of changes in retrieved precipitation from warm clouds is likely due to the reduced ability to detect precipitation from these clouds using the instruments on TRMM.

The point that the average CTT may not adequately constrain the clouds to liquid phase and so may result in the increase in precipitation seen in the shallow cumulus regime over land for the warm clouds has been included in section 3.3.

*c. Considering that the authors make a point of mentioning the importance of isolating different regimes, it is somewhat surprising that regional variations are only briefly discussed in less than 1.5 pages of the manuscript. One obvious problem with using regionally-varying definitions of high and low AI defined based on local PDFs is that precipitation susceptibility might be expected to depend on the background aerosol concentrations typical of the region. Regional results should, therefore, be preferred over global results that mix sensitivities to different magnitudes of aerosol perturbations and different baseline conditions. I would suggest highlighting/contrasting specific regions with different background aerosol concentrations or recasting some of the global results in terms of the mean AI to highlight this effect and demonstrate that aerosol signatures are not simply being washed out by mixing aerosol regimes.*

The main reason that we do not go into further detail about the strength of the observed relationships in different geographical locations is due to the importance of the mean precipitation in determining the difference in precipitation between the high and low AI populations. In regions with a large mean precipitation and so large variance in precipitation, there is a large difference in precipitation between the high and the low AI populations. This regional variation in meteorology hides the majority of the effect of any regional variation of aerosols.

It is difficult to determine much from the regional signals, apart from the (admittedly weak) relationship between mean AI and the difference in precipitation between the high and low AI populations. This could indicate a varying influence of aerosols on precipitation in different locations, but it is hard to pin down. This would be a good topic for investigation in future work with an improved methodology.

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