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Atmospheric Chemistry and Physics
Discussions

Interactive comment on "Wet scavenging limits the detection of aerosol–cloud–precipitation interactions" *by* E. Gryspeerdt et al.

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Reviewer 1*: This manuscript addresses the important problem of what can be implied from the observed relationship between aerosols and cloud properties from spaceborne sensors. Most studies have, either explicitly or implicitly, assumed that positive correlations between aerosol optical depth (AOD) and cloud cover imply a causal relationship whereby the cloud changes are a response to the differing aerosol state. But we know that aerosols are themselves affected by clouds, most importantly through their removal by precipitation (here termed "wet scavenging"). This study uses a combination of observations and numerical modeling to show that aerosol properties are significantly impacted by wet scavenging, but that much of the impact of clouds on*

aerosols is confined to the region below the clouds themselves, which would not be detectable from space because these rely on clear-sky conditions. This is a generally well-written manuscript, with a few exceptions, describing a strong piece of work. This is one of a handful of recent papers that are undertaking the noble task of trying to better understand what processes are driving the AOD-cloud correlations seen in spaceborne data. I support its publication in Atmospheric Chemistry and Physics subject to some revision.

Reply: We thank the reviewer for their comments and address them each in turn below.

MAIN POINTS:

1.*: For the modeling study, the obvious omission to me is a case without wet scavenging, or at least one where is it significantly perturbed. For example, the low aerosol extinction values below cloud in Fig. 5 could simply be caused by penetrative downdrafts bringing clean air from aloft. Such downdrafts are quite common in deep convection. In addition, the conceptual model of Houze (1989) has downward moving air passing toward the storm center from the rear, and this too would be bringing air from aloft down to lower levels. How do the authors know that the low extinction values below the center of the precipitating cloud system are caused by wet scavenging? This is a fundamental tenet of the study and no evidence is provided to support it.*

Reply: We have since performed simulations of the same region with the wet scavenging of aerosols turned off. We find that there is an increase in AOD at the centre of the storm (due to aerosol humidification), rather than the decrease observed when wet-scavenging is active. A composite similar to that shown in Fig. 5 is also now included in the results section (Fig. 6). We believe that this shows that wet scavenging (at least in this model) is the leading cause of the reduction in AOD at the centre of the composite convective system.

2.*: The authors point out important differences in the "all-sky" aerosol assessments (e.g. from MACC) with the "clear sky" aerosol from MODIS, but the study really would* *benefit from a simulation with a high enough resolution that it could be used to directly compare AOD-cloud relationships for all-sky with clear-sky aerosol.*

Reply: We agree that the ideal experiment to perform would be a high resolution, convection resolving simulation of the tropics so that the all-sky and the clear-sky aerosol could be directly compared. Unfortunately, we do not have access to a simulation of the necessary length, resolution and domain size to compare the AOD-precipitation relationships in this way. Additionally, the relationships between precipitation and aerosols are not well understood, so it is not clear that a modelling study would be able to represent all the necessary processes. We hope that such a study could be performed in the future to gain a more complete picture of the differences between all-sky and clear-sky AOD.

***3.**: The shift from the modeling study (section 3.1) to observations (3.2) is too abrupt. The observations are not even from the same region as the modeling study, but seem to include the entire tropics, most of which is over the ocean rather than the land in the observational study. I find this switch to be quite confusing. I couldn't really follow the arguments about wet scavenging in section 3.2. The text in this section appears to fall into the "causality trap" that the authors are trying to warn against. Maybe I missed some key point, but I found this part very confusing as to what the authors are trying to say.*

Reply: We have separated the observational part into a new section and improved the link between the sections, providing a mini-introduction as to why it is necessary and what it is trying to show.

The observational part of this work tries to avoid meteorological covariations being responsible for the observed relationships (and the associated "causality trap") by normalising by CF at the time of the AOD retrieval (along with other meteorological parameters). This normalising by CF aims to reduce the influence of aerosol humidification, so that any underlying relationship between aerosol and precipitation can be examined (Gryspeerdt et al., 2014a). Here, we use MACC to provide a modelled "all-sky"

AOD. Although we are limited from demonstrating that the "clear-sky" is definitely more useful by our inability to simulate the whole tropics at the necessary resolution, this observational study provides some evidence that the "clear-sky" AOD is more useful, as it is able to detect an effect consistent with aerosol invigoration, while the "all-sky" AOD is not (it is heavily affected by wet scavenging).

***4.**: The post-storm "wake" of low AOD seen in Fig. 5 seems to warrant more mention. How much further behind the storm does it extend (it reaches the edge of the composite domain and so would be expected to extend further). Surely, these wet-scavenged clear sky AOD values would be observable from space. For example, P6870, line 6-8. The authors appear to be arguing that using clear sky AOD is better for inferring aerosol impacts on precipitation. But don't such clear sky measurements include the storm wake, where scavenging has played an important role? The authors need to back up their assertion that clear sky AOD is more useful with model simulations that demonstrate it. It seems far too speculative to me. Why is meteorological covariation not an issue?*

Reply: It is hoped that these wet scavenged regions are visible from space and this is a topic of current research. However, the impact of the post-storm "wake" on the surrounding clear-sky AOD is much smaller than the impact of precipitation on the "cloudy-sky" AOD. Whilst the reduced AOD region make up around 30% of the "cloudy-sky" region, it is perhaps 10% of the "all-sky" region and a smaller proportion still of the "clear-sky" region. Some previous studies have shown that the clear-sky AOD correlates more strongly with precipitation than the all-sky AOD (Grandey et al., 2014), but much of this effect could be due to aerosol humidification or meteorological covariations. The "wake" itself does extend further than the edge of the domain, it keeps the same width to around 300 km behind the composite system, where it then becomes difficult to distinguish. However, it is unclear how far it actually extends in practice, as effects due to the finite size of the simulation domain start to play a role. A comment on this has been included in the discussion section (Sect. 4.1).

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5. P6871, line 17.: *What on earth is an "invigoration-like effect"? Is there a "wet scavenging-like effect" to parallel this? What would it be?*
Reply: This was a rather clumsy way of referring to the increased precipitation from the high AOD population at times after the AOD retrieval, which is consistent with, but not necessarily due to, aerosol invigoration.

OTHER ISSUES:

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1. P6853, line 27.: *Chand et al. (2012) concludes the same as the Quaas and Grandey papers.*
Reply: Added

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2. P6847, line 8-10.: *Why is the indirect effect of aerosols on clouds expected to be much weaker than the wet scavenging effects? I thought that the whole idea is that understanding the wet scavenging effects is needed to help understand the indirect effects. If the latter are negligible then what is the purpose of this study?*
Reply: We expect the influence of wet scavenging on aerosols to be stronger than the effects of aerosol on precipitation following previous studies investigating the AOD-CF and AOD-precipitation relationship using GCMs (Quaas et al., 2010; Grandey et al., 2013, 2014). As wet scavenging is the primary method for removing aerosols from the atmosphere, but aerosols are not thought to be the primary control on precipitation occurrence, we feel this is a reasonable assumption. The purpose of investigating wet scavenging in this work is to improve our understanding of how it controls the relationship between AOD and cloud properties, to better understand the difference between models and satellite observations. This then leads to improved estimates of the influence of aerosols on clouds.

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3. P6849, line 14.: *"data are"*
Reply: Amended

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4. Figure A2.: *I would have expected more water than dry aerosol mass. Radius growth factors of 2 are not uncommon, which implies almost an order of magnitude more water in the aerosol than other material.*
Reply: It is possible that the low water content is due to a large amount of hydrophobic aerosol in this region, as the main aerosol source is biomass burning. The weak relationship between AOD and precipitation rate in the Congo region in Fig. 1 might also suggest that aerosol humid growth is weaker here (or wet scavenging is stronger), perhaps due to the aerosol content. This low growth factor would not affect the results in this work relative to wet scavenging, but might result in a lower increase in AOD due to aerosol humidification in the cloudy regions compared to the global average.

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5. P6864, line 15.: *What "regimes" are being discussed here?*
Reply: These are the different cloud regimes included in Fig. 6. This has now been amended.

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6. P6865, line 22:: *How exactly is wet scavenging "observed" here? Also, P6866 line 25 talks of "observation of wet scavenging", but I don't know what observation they are referring to.*
Reply: Unfortunately, we cannot observe the physical scavenging of the aerosol, so this is really "observations consistent with wet-scavenging". The observations referred to are the plots in Fig. 6. Clouds which are observed to have a low AOD at the time of the AOD retrieval are found to have a higher mean precipitation rate over the previous 12 hours than clouds with a high retrieved AOD (the blue line is above the red line). While this is not conclusive, it is the relationship that would be expected if wet scavenging was significantly impacting the aerosol population.

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7. P6866, line 3-4.: *How is the invigoration effect "observed" here? Are the authors concluding the opposite of their title statement? I was losing steam by this point and was a little confused about whether the authors are arguing for an invigoration effect in* *shallow cumulus which probably don't even contain ice (and therefore how can there be an invigoration effect as outlined by Rosenfeld?).*

Reply: We thank the reviewer for pointing this out. This part of the paper appears to be short on some of the explanation that was necessary in previous work. The important point here is that while the regimes are labelled as “shallow cumulus” and “thick mid level”, these names only refer to the cloud types at the time of the aerosol retrieval (as that is also when the cloud properties are retrieved). The clouds can develop after the aerosol retrieval and the observed increase in precipitation is likely to come from the clouds that transition into the deep convective regime. As shown in Gryspeerdt et al. (2014a), there is little change in precipitation from clouds which remain below the freezing level, implying (as the reviewer has pointed out) that occurrence of ice is a important factor. As with the wet scavenging, this is only a result that is consistent with aerosol invigoration, rather than an observation of it. Further explanation has been included in the text to explain the names of the regimes and the possibility of regime transitions occurring after the AOD retrieval.

References

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