Atmos. Chem. Phys. Discuss., 15, C3029–C3036, 2015
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Atmospheric Chemistry and Physics Discussions

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15, C3029–C3036, 2015

Interactive Comment

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

E. Gryspeerdt et al.

edward.gryspeerdt@uni-leipzig.de

Received and published: 28 May 2015

***Reviewer 3**: This manuscript examines the relationship between AOD and precipitation in GCMs and satellite retrievals. Satellite retrievals show a positive correlation between clear sky AOD and adjacent precipitation in most tropical and subtropical locations, but AOD and precipitation retrievals are non-coincident. In GCMs, AOD is an "all sky" variable rather than a "clear sky" variable, and the AOD-precipitation relationship is different than in satellite retrievals. With the aid of a 3-week mesoscale simulation of deep convective systems in the Congo, the authors show that this is a result of wet scavenging of aerosols. The aerosols ingested into the deep convective updrafts come from nonscavenged regions, which supports the use of satellite clear sky retrievals of*

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AOD in inflow regions adjacent to convective clouds and precipitation. Further support comes from the lack of a positive AOD-precipitation relationship in a high CF thick mid-level cloud regime when the MACC reanalysis AOD is used instead of MODIS AOD. The strongest part of the paper is the demonstration of wet scavenging producing different AOD-precipitation relationships in GCMs and satellite retrievals. The weakest is the hand wavy discussion of "invigoration" in shallow cumulus and thick mid-level cloud regimes, as discussed more in comments below. Overall, this is a manuscript on the important but complicated topic of aerosol impacts on precipitation, and it is worthy of publication in ACP, but only following revisions.

Reply: We thank the reviewer for their comments and have address them below

MAJOR COMMENTS

***1.**: Sections 2.3 and 3.2 are confusing, and there needs to be better transitions from and connections to the simulation result sections (e.g., Sections 2.2 and 3.1). Here are a couple examples from the observations results that did not make sense to me:*

***a**: . You ensure that high and low AOD quartiles have the same distributions of CF and meteorology at T+0 for different cloud regimes and claim that changes in precipitation before and after T+0 are the result of aerosol interactions. Why can't meteorology or CF change before or after T+0 and be responsible for differences in precipitation rather than aerosols?*

Reply: This is a good point, which Gryspeerdt et al. (2014a) attempted to cover. The normalisation by CF is really intended to assist in normalising by meteorology, as it may be a better indicator of local relative humidity than the reanalysis RH. It is true that the normalisation at the time of the AOD retrieval may not actually restrict the local meteorology enough to conclude that the resulting precipitation development changes are due to an aerosol impact of cloud processes. However, it appears that the normalisation (especially by CF) does act to significantly reduce the impact of meteorological covariations. An analysis of the development of 500hPa vertical velocity before and af-

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ter the AOD retrieval indicated that the normalisation by meteorological parameters removed any significant difference in the development of the meteorological parameters, indicating that normalising at T+0 is a reasonable attempt at removing the influence of meteorological covariations (Gryspeerdt et al., 2014a).

***b.**: Controlling for 850 hPa relative humidity, 500 hPa pressure vertical velocity, 10 m/s wind speed, and LTSS (from Gryspeerdt et al. 2014) does not control for all meteorological factors that impact precipitation. What about variables that directly impact rainfall such as precipitable water or variables that directly impact convection such as CAPE and vertical wind shear? Without controlling for these variables, the claim that an aerosol invigoration effect is occurring is unsubstantiated.*

Reply: Obviously to demonstrate that aerosol is responsible for the precipitation increase, it is necessary to normalise by all atmospheric variables. Unfortunately, this restricts the data volume too severely and so we had to make some choices. The variables chosen (850 hPa RH and 500hPa vertical velocity) were picked because of their previous links to both aerosol and cloud processes. While CAPE is important for convective cloud processes, its connection to aerosol and AOD is much more tenuous.

The normalisation by CF actually does the majority of the "work", providing a significant advance over previous attempts to account for meteorological covariations, although it is still possible that aerosol humidification is playing a role in the observed relationships. From previous labbooks, normalisation by ECMWF precipitable water was tried in Gryspeerdt et al. (2014a), but it had much the same effect as normalising by 850hPa RH and so was omitted from the final analysis.

***c.**: If there were an aerosol invigoration effect, you'd expect to see it in the deep convective regime where updrafts are strong enough to loft liquid into the mixed phase zone so that freezing can be enhanced. An increase in aerosols should reduce the probability of warm rain precipitation in shallow cumulus (since they don't contain ice) because increased CCN reduces cloud droplet size, so aerosol invigoration of precip-*

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itation doesn't make sense for these clouds. Thick mid-level clouds are presumably stratiform rainfall in mesoscale convective systems and frontal type systems. Again, little cloud water is lofted in this cloud type, so how does aerosol invigoration operate?
Reply: This is due to the method of naming the regimes, something which isn't covered well in this paper (and so has been added to the methods section). The issue is that the cloud types are determined at the same time as the AOD retrieval. This is the only time they are guaranteed to be in this regime (and they often transition between regimes over a short period of time due to the diurnal cycle - Gryspeerdt et al., 2014b). The shallow cumulus clouds themselves probably aren't the ones generating the increase in precipitation, indeed, Gryspeerdt et al. (2014a) showed that if the cloud tops are restricted to being below the freezing layer, there is relatively little difference between precipitation development of the high and low AOD populations (highlighting the importance of cloud ice). It is also important to note that the clustering method used to determine the regimes does not limit the shallow cumulus regime to only shallow clouds, some clouds with higher tops are included.

***d.**: To examine large deep convective systems in the Congo with a simulation and then global shallow cumulus and thick mid-level clouds regimes with observations is part of what contributes to the confusion when transitioning between sections of the paper. Since most of the precipitation in the tropics is from deep convection, and this is the regime where one would theoretically most expect an aerosol invigoration effect, why not include this regime in the observational analysis?*
Reply: As noted above the observations do study the precipitation from deep convective clouds, but this is not obvious, as the names of the regimes are determined by the cloud type retrieved at T+0. The explanation of this has been improved in the method and observations sections.

***2.**: Can you clarify what you mean by an invigoration-like effect? I'm assuming that you are referring to the dynamical invigoration of convection by increased lofting and freez-*

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ing of cloud water (as hypothesized by Rosenfeld), but there are a lot of steps missing between what you have shown and concluding that this type of an effect is increasing precipitation. You can certainly hypothesize reasons for increased precipitation with increased clear sky AOD, but you shouldn't be so conclusive without more evidence shown, and you should more clearly lay out what invigoration means and how it might lead to more precipitation. In my mind, I don't see why meteorological conditions that you did not control for at T+0 (see 1b) can't be correlated with AOD and lead to increased precipitation just as easily as the aerosols themselves.

Reply: The term "invigoration-like effect" is just a clumsy way of referring to the increased precipitation after T+0 in the high AOD population. It has been changed where it occurs to refer to an "apparent invigoration effect".

***3.**: Convective downdrafts bring down cleaner air from mid levels into the boundary layer. Can you show that this effect is small relative to wet scavenging in your WRF simulation? Also, although not an issue over the rainforest in the Congo, convective system outflow in arid regions (e.g., the Sahel) often generates large amounts of dust that can increase AOD (e.g., Flamant et al. 2007 (http://onlinelibrary.wiley.com/doi/10.1002/qj.97/abstract)), so the simulation in the Congo region may not be universally representative.*

Reply: A composite from a simulation without wet scavenging has been included in section 4 of the paper. It shows that without wet scavenging, the reduction in AOD at the centre of the storm is not present.

MINOR COMMENTS

***1.**: This is not a major gripe, but I don't think the title of the paper fits the results you show. First, wet scavenging is an aerosol-cloud-precipitation interaction. Second, you are not examining all aerosol-cloud-precipitation interactions. You are primarily concerned with aerosol-precipitation interactions. Third, these interactions are not being detected by satellite. Correlations are being detected. And lastly, detection isn't limited*

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in satellite retrievals. It is limited in GCMs. A more specific title would be something like "Wet scavenging limits the detection of aerosol effects on precipitation in GCMs" or "Wet scavenging produces different relationships between AOD and precipitation in satellite retrievals and GCMs".

Reply: Although it is discussed that this might limit the detection in GCMs, the results in this work show the detection of these relationships being limited in a reanalysis/observations combined study, so specifying GCMs in the title might not be correct. Indeed, due to their ability to run multiple realisations of the same climate with different aerosol perturbations, it is relatively straightforward to detect aerosol effects on precipitation in models. However, we agree with the point that wet scavenging is an interaction between aerosol and precipitation. The title has therefore been changed to "Wet scavenging limits the detection of aerosol effects on precipitation."

2.: *You mention the uncertainty associated with modes of convection that are different than your composite mode from the WRF simulation, but what about uncertainty in the scavenging of aerosols that contribute to AOD that are not present in the Congo? Is scavenging of biomass burning aerosols representative of scavenging of other aerosols such as dust? Is scavenging of boundary layer aerosols representative of scavenging of free tropospheric aerosols plumes?*

Reply: This is a good point and one not really covered in this work. However, the previous work by Grandey et al. (2014) using a GCM suggests that wet scavenging is also important at larger scales. They find that when running a GCM with and without convective wet scavenging, the relationship between AOD and precipitation in the model is reversed, almost globally. As this occurs even over ocean, and far from the main aerosol sources, this would in turn suggest that wet scavenging is also important for aerosols that have been transported long distances or in the free atmosphere. This has now been noted in the results (Sect. 3.2).

3.: *Does your WRF simulation reintroduce aerosols into the atmosphere when cloud*

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and rain droplets evaporate? If not, removal of aerosol could be overestimated.
Reply: The convective transport scheme, which handles the convective wet scavenging, also reintroduces aerosol from evaporating rainwater.

***4.**: Do you have a citation for the last sentence of the second paragraph in Section 4 (stating that aerosol hygroscopic growth generates much of the positive correlation between clear sky AOD and precipitation)?*
Reply: We have now included the citations (Boucher and Quaas, 2012; Grandey et al., 2014).

***5.**: It seems strange to have a Section 4 (Discussion) and Section 4.1 (Comparison to GCM processes) without a 4.2. Maybe change Section 4.1 to Section 5 or have the first part of Section 4 as Section 4.1 with the comparison to GCM processes as Section 4.2.*
Reply: Amended

***6.**: Can you explain what you mean by relative frequency of occurrence (RFO)?*
Reply: This term was from earlier work and has been removed as it occurs only once. The sentence now reads: "These high CF/strongly precipitating regimes occur rarely, with only 13% of the cloud regime occurring in the tropics falling into the deep convective or thick mid-level regimes (Gryspeerdt and Stier, 2012)."

***7.**: At the beginning of Section 4.1, you should change "air is drawn into convective updraughts from non-precipitating regions" to "air is usually drawn into convective updraughts from non-precipitating regions".*
Reply: Amended

***8.**: Can you provide a citation for the last sentence in the second paragraph of the conclusions (aerosol hygroscopic growth primarily causes the increased in AOD with*

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increasing precipitation in scenes with low precipitation)?

Reply: This is shown in supplementary Figure A1 (a reference to this figure is now included). There is not a specific study that we are aware of that covers this for low precipitation rate situations, but it is covered more generally by (Boucher and Quaas, 2012) and (Grandey et al., 2014) who examine the link between AOD and precipitation.

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