Rainfall-aerosol relationships explained by wet scavenging and humidity

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Abstract Relationships between precipitation rate and aerosol optical depth, the extinction of light by aerosol in an atmospheric column, have been observed in satellite-retrieved data. What are the reasons for these precipitation-aerosol relationships? We investigate relationships between convective precipitation rate \( R_{\text{conv}} \) and aerosol optical depth \( \tau_{\text{tot}} \) using the ECHAM5-HAM aerosol-climate model. We show that negative \( R_{\text{conv}} \tau_{\text{tot}} \) relationships arise due to wet scavenging of aerosol. The apparent lack of negative \( R_{\text{conv}} \tau_{\text{tot}} \) relationships in satellite-retrieved data is likely because the satellite data do not sample wet scavenging events. When convective wet scavenging is excluded in the model, we find positive \( R_{\text{conv}} \tau_{\text{tot}} \) relationships in regions where convective precipitation is the dominant form of model precipitation. The spatial distribution of these relationships is in good agreement with satellite-based results. We further demonstrate that a substantial component of these positive relationships arises due to covariation with large-scale relative humidity. Although the interpretation of precipitation-aerosol relationships remains a challenging question, we suggest that progress can be made through a synergy between observations and models.

1. Introduction

Atmospheric aerosols, which behave as cloud condensation nuclei, are “a critical factor in the atmospheric hydrological cycle and radiation budget” [Tao et al., 2012]. Nevertheless, “it has proved frustratingly difficult to establish climatically meaningful relationships among the aerosols, clouds and precipitation” [Stevens and Feingold, 2009].

Correlations between satellite-retrieved aerosol, cloud, and precipitation properties have been reported [Koren et al., 2005; Sorooshian et al., 2009; Yuan et al., 2011; Koren et al., 2012; Grysspeerdt et al., 2014a]. However, establishing causality is difficult due to the complexity of the system. There are many possible explanations for relationships between satellite-retrieved aerosol properties (such as aerosol optical depth, \( \tau_{\text{tot}} \)) and cloud-related properties (such as precipitation rate or cloud fraction) [Grandey et al., 2013a; Quaas et al., 2010]: genuine aerosol indirect [Albrecht, 1989] and semidirect [Ackerman, 2000] effects on clouds; cloud processing of aerosols, including aerosol hygroscopic growth in the immediate vicinity of clouds [Koren et al., 2007]; wet scavenging of aerosol by precipitation; humidity driving aerosol hygroscopic growth and cloud properties [Quaas et al., 2010; Chand et al., 2012; Grandey et al., 2013a; Boucher and Quaas, 2013]; other meteorological factors such as local winds [Engström and Ekman, 2010] and large-scale synoptic systems [Grandey et al., 2013b]; climatological spatial and temporal gradient effects [Grandey and Stier, 2010]; and satellite retrieval errors, such as cloud contamination of \( \tau_{\text{tot}} \) [Huang et al., 2011]. Furthermore, relationships between an aerosol property and a cloud property might be mediated via relationships with a second cloud property [Grysspeerdt et al., 2014b].

Koren et al. [2012] found positive relationships between Tropical Rainfall Measuring Mission (TRMM) rain rate and Moderate Resolution Imaging Spectroradiometer (MODIS) \( \tau_{\text{tot}} \) across most of the tropics and mid-latitudes. By excluding \( \tau_{\text{tot}}>0.3 \) and conducting further analysis of data sorted by cloud fraction, they contended that the relationships are unlikely to be an artifact due to cloud contamination of \( \tau_{\text{tot}} \). After performing analysis of the data sorted by pressure vertical velocity in an attempt to account for covariation with meteorology, they found that the relationships remained, although a component of the relationships “might still be due to environmental conditions” [Koren et al., 2012]. Based on these results, and associated
changes in cloud top height, Koren et al. suggested that “the invigoration of clouds and the intensification of rain rates is a preferred response to an increase in aerosol concentration” [Koren et al., 2012].

Koren et al. pointed out that the TRMM rain rate may be most sensitive to precipitation intensities greater than 1 mm/h, intensities that are often associated with convective precipitation. Hence, their results are consistent with the aerosol convective invigoration hypothesis [Andreae et al., 2004; Rosenfeld et al., 2008] and do not negate the possibility that aerosols may suppress precipitation in weakly precipitating clouds [Albrecht, 1989]. However, as mentioned above, conclusively establishing causality is a difficult problem when investigating relationships between satellite-retrieved aerosol, cloud, and precipitation properties.

Following the publication of the paper by Koren et al. [2012], Boucher and Quaas [2013] used ECHAM5-HAM simulations to demonstrate that “aerosol humidification has a large impact on the relationship between $\tau_{\text{tot}}$ and rain rate” [Boucher and Quaas, 2013]. In response, Koren et al. [2013] used hygroscopic growth and radiative transfer calculations to show that aerosol humidification cannot account for the $\tau_{\text{tot}}$ variation in the MODIS satellite-retrieved data. But although it may be true that relative humidity cannot explain a large component of observed variation in $\tau_{\text{tot}}$, this does not necessarily imply that humidity cannot explain a large component of observed covariation between $\tau_{\text{tot}}$ and precipitation. If humidity affects both precipitation and $\tau_{\text{tot}}$ to some extent (even just a small extent), then it is possible that humidity might be able to explain a larger component (possibly all) of the covariation of $\tau_{\text{tot}}$ and precipitation.

Nevertheless, in order to assess whether ECHAM5-HAM is a suitable tool for investigating these relationships, we should question how well ECHAM5-HAM captures the observed variation in $\tau_{\text{tot}}$. We discuss this in the supporting information. In our ECHAM5-HAM control simulation, the variation in $\tau_{\text{tot}}$ is similar to that found in satellite-retrieved MODIS data. To further address the concerns of Koren et al. [2013], we demonstrate that humidity is not the primary driver of $\tau_{\text{tot}}$ variation in ECHAM5-HAM. (See the supporting information for details.)

One shortcoming of the analysis by Boucher and Quaas [2013] is that they found negative relationships between $\tau_{\text{tot}}$ and precipitation rate in the tropics, in disagreement with the results of Koren et al. [2012]. They suggested that the disagreement is “most likely due to the scavenging of aerosols by rain” [Boucher and Quaas, 2013]. In this paper, we demonstrate that this is indeed the case. After correcting for the associated sampling difference between the model and the satellite-retrieved data, we find that the modeled relationships are in much better agreement with the relationships reported by Koren et al. [2012]. We then proceed to investigate the contribution of relative humidity to relationships between $\tau_{\text{tot}}$ and precipitation.

2. Method

2.1. Model Simulations

The model data used in this paper are from two ECHAM5.5-HAM2.0 [Stier et al., 2005; Zhang et al., 2012] general circulation model simulations [Grandey et al., 2013a]: a control simulation, and a “NoConvScav” simulation with no wet scavenging of aerosols by convective precipitation. The simulations are run at T63 horizontal resolution (corresponding to approximately 1.9° × 1.9°), with 31 levels vertically. They both use the Sundqvist stratiform cloud cover scheme [Sundqvist et al., 1989]. The HAM aerosol module [Stier et al., 2005; Zhang et al., 2012] has been coupled with the cloud microphysics scheme in order to simulate the cloud albedo and cloud lifetime indirect aerosol effects [Lohmann et al., 2007]. The Abdul-Razzak and Ghan activation scheme [Abdul-Razzak and Ghan, 2000] is used. However, aerosol microphysical effects on convection are not represented. Both simulations use present-day aerosol and precursor emissions for the year 2000. The meteorological fields are nudged toward European Centre for Medium-Range Weather Forecasts Re-Analysis (ERA-40) data, starting in October 1999 and finishing at the end of December 2000 [Zhang et al., 2012]. Data from these simulations have previously been used to investigate relationships between aerosol optical depth and cloud fraction [Grandey et al., 2013a].

In order to allow comparison with the results of Koren et al. [2012], and in order to reduce interseasonal temporal gradient effects, only data from June-July-August (JJA) are used in this paper. The effective spin-up period is 8 months—this is much longer than the typical aerosol lifetimes of less than a week for the control simulation [Stier et al., 2005] and less than 3 weeks for the NoConvScav simulation [Grandey et al., 2013a].
2.2. Aerosol Optical Depth and Precipitation Rate Model Data
Aerosol and precipitation data are output at 6 h resolution. Two aerosol optical depth ($\tau$) output variables are used in this paper: total aerosol optical depth ($\tau_{\text{tot}}$), and dry aerosol optical depth ($\tau_{\text{dry}}$), diagnosed by reducing the optical extinction coefficient of each aerosol mode by the water volume fraction for that mode [Quaas et al., 2010; Grandey et al., 2013a]. The latter, $\tau_{\text{dry}}$, is an approximation of the aerosol optical depth that would be measured if the aerosols did not swell hygroscopically. Hence, $\tau_{\text{dry}}$ is independent of relative humidity. ECHAM5 diagnoses two types of precipitation rate ($R$): stratiform large-scale precipitation rate and convective precipitation rate. Both total precipitation rate ($R_{\text{tot}}$; the sum of stratiform and convective precipitation rate) and convective precipitation rate ($R_{\text{conv}}$) are used in this paper (Figure 1). As mentioned above, only JJA data are used here.

2.3. Differences Between “Clean” and “Polluted” Conditions
Following Koren et al. [2012], clean and polluted conditions are defined based on $\tau$ (either $\tau_{\text{tot}}$ or $\tau_{\text{dry}}$): clean conditions are where $\tau$ is less than the 33rd percentile for that grid box and data set, and polluted conditions are where $\tau$ is greater than the 67th percentile for that grid box and data set. Koren et al. [2012] apply a $\tau$ threshold in an attempt to reduce the cloud contamination errors that may occur in satellite-retrieved $\tau$ data. However, this requirement is unnecessary for model data, and it is not applied here because it would introduce a sampling bias between $\tau_{\text{tot}}$ and $\tau_{\text{dry}}$ due to the fact that $\tau_{\text{dry}}$ is generally much smaller than $\tau_{\text{tot}}$. For each data set and grid box, the mean $R$ (either $R_{\text{tot}}$ or $R_{\text{conv}}$) is calculated for the clean and polluted conditions. All $R$ data, including those where $R$ is zero, are included. The $R$ differences (polluted – clean) can then be displayed on maps (Figure 2). The area-weighted mean differences are given in Table 1.

2.4. Correlation Coefficients
To complement the precipitation rate differences, linear correlation coefficients ($r$) between $\tau$ and $R$ are also calculated for each grid box. The area-weighted mean $r$ values are given in Table 1, and the maps can be seen in Figure S3 in the supporting information. Weighted mean $r^2$ values, weighted by precipitation amount ($R \times \text{area}$), are also given in Table 1. This weighted mean $r^2$ shows the proportion of the total variance in $R$ that can be explained by the $R$-$\tau$ linear relationship.

3. Results and Discussion
Figure 1a shows the mean June-July-August (JJA) total precipitation rate ($R_{\text{tot}}$) for the ECHAM5-HAM control simulation. (It is worth noting that this configuration of ECHAM5-HAM contains a representation of aerosol indirect effects on stratiform clouds but not on convective clouds.) Although there are some discrepancies, such as the split Intertropical Convergence Zone in the western Pacific ocean, the modeled distribution is in good agreement with TRMM satellite-retrieved data (Figure S2 in the supporting information).
Figure 2. Maps of the differences in precipitation rate between clean and polluted conditions during June-July-August. (a) Difference in total precipitation rate ($R_{\text{tot}}$) between clean (total aerosol optical depth $\tau_{\text{tot}} < 33\text{rd percentile}$) and polluted ($\tau_{\text{tot}} > 67\text{th percentile}$) conditions for the control simulation. (b) Similar to Figure 2a but for convective precipitation rate ($R_{\text{conv}}$) instead of $R_{\text{tot}}$. (c) Similar to Figure 2b but for the NoConvScav simulation. (d) Similar to Figure 2c but for dry aerosol optical depth ($\tau_{\text{dry}}$) instead of $\tau_{\text{tot}}$. The annotated arrows show the conceptual steps linking each subfigure. White indicates differences of exactly zero, which arise due to an absence of model convective precipitation in some places. Area-weighted means are provided at the side of each figure and are summarized in Table 1. Similar maps of correlation coefficients are shown in Figure S3 in the supporting information.

Figure 2a shows the JJA $R_{\text{tot}}$ difference between clean and polluted conditions, categorized according to the local 33rd and 67th percentiles of total aerosol optical depth ($\tau_{\text{tot}}$), for the control simulation. The dominance of blue shading in the tropics and midlatitude storm tracks, where $R_{\text{tot}}$ is large (Figure 1a), indicates negative $R_{\text{tot}} - \tau_{\text{tot}}$ relationships. These strong negative relationships in the tropics and extratropical storm track regions lead to a negative global mean difference (Table 1).

As mentioned earlier, the TRMM satellite data used by Kobane et al. [2012] may be most sensitive to precipitation intensities associated with convective precipitation. In the ECHAM5-HAM model, convective precipitation rate ($R_{\text{conv}}$) is diagnosed separately from the large-scale stratiform precipitation rate. With the

Table 1. Global Area-Weighted Mean Relationships Between Precipitation Rate and Aerosol Optical Depth During June-July-August

<table>
<thead>
<tr>
<th>ECHAM5-HAM Simulation</th>
<th>Type of Precipitation Rate ($R$)</th>
<th>Type of Aerosol Optical Depth ($\tau$)</th>
<th>$R$ Difference (Polluted − Clean; mm/h), Weighted by Area</th>
<th>Correlation ($r$), $r^2$, Weighted by $R \times \text{Area}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>$R_{\text{tot}}$</td>
<td>$\tau_{\text{tot}}$</td>
<td>−0.119</td>
<td>−0.100</td>
</tr>
<tr>
<td>Control</td>
<td>$R_{\text{conv}}$</td>
<td>$\tau_{\text{tot}}$</td>
<td>−0.085</td>
<td>−0.053</td>
</tr>
<tr>
<td></td>
<td>$R_{\text{conv}}$</td>
<td>$\tau_{\text{tot}}$</td>
<td>+0.079</td>
<td>+0.164</td>
</tr>
<tr>
<td></td>
<td>$R_{\text{conv}}$</td>
<td>$\tau_{\text{dry}}$</td>
<td>+0.033</td>
<td>+0.073</td>
</tr>
</tbody>
</table>

$R_{\text{tot}}$ is total precipitation rate, $R_{\text{conv}}$ is convective precipitation rate, $\tau_{\text{tot}}$ is total aerosol optical depth, and $\tau_{\text{dry}}$ is dry aerosol optical depth. Annotations show the conceptual steps linking each row.
aim of interpreting the results of Koren et al. [2012], we now focus on $R_{\text{conv}}$ rather than $R_{\text{tot}}$. Focusing on $R_{\text{conv}}$ provides an advantage in allowing investigation of the role of wet scavenging by convective precipitation, as will be discussed later.

Figure 1b shows the component of the JJA precipitation rate arising due to convection ($R_{\text{conv}}$). Comparison with Figure 1a reveals that $R_{\text{conv}}$ dominates in the tropics, whereas stratiform precipitation dominates in the midlatitudes.

Figure 2b shows the JJA $R_{\text{conv}}$ difference between clean and polluted conditions for the control simulation. In the tropics, the strong negative $R_{\text{conv}}-\tau_{\text{tot}}$ relationships are almost identical to the $R_{\text{tot}}-\tau_{\text{tot}}$ relationships (Figure 2a), as would be expected because $R_{\text{conv}}$ is the dominant component of $R_{\text{tot}}$ in the tropics (Figure 1). Outside the tropics, where $R_{\text{conv}}$ is much smaller, the $R_{\text{conv}}-\tau_{\text{tot}}$ relationships are also much weaker.

Koren et al. [2012, Figure 2b] found positive relationships between precipitation rate and $\tau_{\text{tot}}$ for both the tropics and the midlatitude storm tracks in strong disagreement with the control simulation results presented here. One possible explanation for this disagreement in sign may be that the satellite data and model data sample different air masses. In particular, wet scavenging of aerosols by precipitation, which would lead to negative $R_{\text{tot}}-\tau_{\text{tot}}$ and $R_{\text{conv}}-\tau_{\text{tot}}$ relationships, is likely poorly sampled in the satellite data [Grandey et al., 2013a]. Satellite retrievals of $\tau_{\text{tot}}$ can only be made for cloud-free pixels. Aerosol in these cloud-free pixels would likely not have been affected by wet scavenging. Aerosol in regions near cloud and below cloud, including those where precipitation occurs, cannot be seen. Hence, there may be two aerosol populations in any given $1^\circ \times 1^\circ$ grid box: the “satellite-visible” cloud-free aerosol, and the “satellite-invisible” near-cloud and below-cloud aerosol. The former of these contributes to satellite-retrieved $\tau_{\text{tot}}$, whereas it is the latter that may often be depleted by wet scavenging. In contrast, the modeled aerosol is homogeneous across each model grid box, so the aerosol population contributing to modeled $\tau_{\text{tot}}$ may have been depleted by wet scavenging.

We now test the hypothesis that the negative relationships in the model arise due to wet scavenging. One possible approach would be to turn off all wet scavenging in the model. However, wet scavenging is the primary removal mechanism for aerosol in the model, so it may therefore be preferable to allow some wet scavenging to remain. Instead of turning off all wet scavenging, we turn off convective wet scavenging while allowing stratiform large-scale wet scavenging to remain as a sink for the aerosol. We refer to the resulting simulation as the “NoConvScav” simulation. Since only convective wet scavenging has been turned off in the NoConvScav simulation, hypotheses relating to $R_{\text{conv}}$ can be tested with more confidence than those relating to $R_{\text{tot}}$.

Figure 2c shows the JJA $R_{\text{conv}}$ difference between clean and polluted conditions for the NoConvScav simulation. It can be clearly seen that most of the $R_{\text{conv}}-\tau_{\text{tot}}$ relationships are now positive, in contrast to the negative relationships found for the control simulation (Figure 2b). This demonstrates that the negative relationships arose due to convective wet scavenging.

In addition to allowing the wet scavenging hypothesis to be tested, the NoConvScav simulation partially corrects for the sampling differences between the satellite data and the model. Now that convective wet scavenging events are no longer “observed” in the model, there is much better agreement between the model results and the satellite-based results of Koren et al. [2012], particularly in the tropics.

What are the reasons for the positive $R_{\text{conv}}-\tau_{\text{tot}}$ relationships in the NoConvScav simulation? Satellite retrieval errors are not modeled and therefore cannot explain the modeled relationships. Furthermore, aerosol microphysical effects on convective clouds are not modeled and therefore cannot explain the modeled relationships. Although semidirect effects by absorbing aerosols cannot be ruled out, it is unlikely that semidirect effects can explain the positive relationships: semidirect effects would likely lead to negative relationships, and the spatial distribution in Figure 2c does not correlate well with the spatial distribution of aerosol absorption in ECHAM5-HAM [Stier et al., 2007]. Two remaining categories may be able to explain the positive relationships: covariation of $R_{\text{conv}}$ and $\tau_{\text{tot}}$ with relative humidity, and covariation with other meteorology.

The first of these, covariation with relative humidity, can be tested by replacing $\tau_{\text{tot}}$, which includes a water component due to hygroscopic growth, with dry aerosol optical depth ($\tau_{\text{dry}}$), which approximates the aerosol optical depth that would be measured if the aerosols did not swell hygroscopically. The $R_{\text{conv}}-\tau_{\text{dry}}$ results are shown in Figure 2d. It can be seen that the strength of the positive relationships has
decreased compared to Figure 2c. The global mean $\tau_{\text{conv}}$ difference has decreased from $+0.079$ mm/h to $+0.033$ mm/h (Table 1). Similarly, the mean $r^2$ (coefficient of determination), weighted by convective precipitation amount, has decreased from 0.126 to 0.059. This implies that the $\tau_{\text{conv}}$-$\tau_{\text{tot}}$ relationship can explain (statistically, not necessarily causally) almost 13% of the $\tau_{\text{conv}}$ variance, whereas the $\tau_{\text{conv}}$-$r_{\text{conv}}$ relationship can explain only 6% of the $\tau_{\text{conv}}$ variance. These results suggest that relative humidity is a major driver of the $\tau_{\text{conv}}$-$\tau_{\text{tot}}$ relationship.

Positive $\tau_{\text{conv}}$-$\tau_{\text{tot}}$ relationships remain even after relative humidity has been accounted for. These may likely be due to covariation with other meteorological factors not accounted for here.

Aerosol optical depth has been used in this paper in order to facilitate comparison with the satellite-based relationships reported by Koren et al. [2012]. However, some studies investigating cloud-aerosol interactions have used aerosol index instead [e.g., Nakajima et al., 2001; Penner et al., 2011]. It is possible that aerosol index, which is more sensitive to aerosol number concentration, might be less sensitive to relative humidity than $\tau_{\text{tot}}$. Investigation of this possibility may provide a basis for future work.

4. Conclusions

The modeling results we have presented here suggest that wet scavenging and relative humidity are major drivers of precipitation-$\tau_{\text{tot}}$ relationships on a global scale. Similar conclusions can be drawn if correlation coefficients are used to quantify the relationships (Table 1 and Figure S3 in the supporting information) or if a whole year (12 months) of data are used for the analysis (Figure S4 in the supporting information). For the satellite-based results of Koren et al. [2012], satellite-retrieval errors and aerosol effects on convection, neither of which has been directly explored here, may also play a role.

The interpretation of precipitation-aerosol relationships in satellite data remains a challenging question. Using models to help with interpretation of satellite data presents challenges, for example, satellites and models may “observe” different aerosol populations, as we have shown. Nevertheless, we suggest that substantial progress can be made through a synergy between observational data sets and models. Complementary analysis of in situ measurements and cloud-resolving models, neither of which has been used here, could form a basis for future studies.


Quaas, J., B. Stevens, P. Stier, and U. Lohmann (2010), Interpreting the cloud cover aerosol optical depth relationship found in satellite data using a general circulation model, _Atmos. Chem. Phys._, 10(13), 6129–6135, doi:10.5194/acp-10-6129-2010.


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