AGU PUBLICATIONS

Geophysical Research Letters

RESEARCH LETTER

10.1002/2014GL059524

Key Points:
- A strong sensitivity of cloud height to aerosol optical depth is found globally
- Cloud fraction controls the majority of the strength of this sensitivity
- The cloud top height-aerosol sensitivity is smaller than previously thought

Correspondence to:
E. Gryspeerdt,
gryspeerdt@atm.ox.ac.uk

Citation:
Gryspeerdt, E., P. Stier, and B. S. Grandey (2014), Cloud fraction mediates the aerosol optical depth-cloud top height relationship, *Geophys. Res. Lett.*, *41*, 3622–3627, doi:10.1002/2014GL059524.

Received 6 FEB 2014
Accepted 15 APR 2014
Accepted article online 22 APR 2014
Published online 19 MAY 2014

Cloud fraction mediates the aerosol optical depth-cloud top height relationship

E. Gryspeerdt[1], P. Stier[1], and B. S. Grandey[2]

[1] Department of Physics, University of Oxford, Oxford, UK, [2] Center for Environmental Sensing and Modeling, Singapore-MIT Alliance for Research and Technology, Singapore

Abstract The observed strong link between aerosol optical depth (τ) and cloud top pressure (p_{top}) has frequently been interpreted as the invigoration of convective clouds by aerosol, with increased τ being strongly correlated with decreases in p_{top} (increases in cloud top height). A strong correlation between τ and cloud fraction (f_c) has also been observed. Using satellite-retrieved data, here we show that p_{top} is also strongly correlated to f_c, and when combined with the strong sensitivity between f_c and τ, a large proportion of the relationship between p_{top} and τ can be reconstructed. Given the uncertainties about the influence of aerosol-cloud interactions on the τ-f_c relationship, this suggests that a large fraction of the τ-p_{top} correlation may not be due to aerosol effects. Influences such as aerosol humidification and meteorology play an important role and should therefore be considered in studies of aerosol-cloud interactions.

1. Introduction

A strong correlation between aerosol optical depth (τ) and cloud top pressure (p_{top}) is observed globally [*Koren et al.*, 2005, 2010a; *Yuan et al.*, 2011; *Niu and Li*, 2012]. Different measurements of cloud top height, both passive radiometer based [*Koren et al.*, 2005, 2010a] and active instrument based [*Yuan et al.*, 2011; *Niu and Li*, 2012], show an increase in cloud top height (decrease in p_{top}) with increased τ. The correlation between τ and p_{top} has been suggested as evidence for an aerosol invigoration of convective clouds [*Koren et al.*, 2005]. By increasing the number and decreasing the size of cloud droplets, suppressing precipitation in the liquid phase, aerosols may be able to increase latent heat release from the freezing of the cloud water, increasing the buoyancy of cloud parcels and invigorating convective clouds [*Williams et al.*, 2002; *Rosenfeld et al.*, 2008]. Due to the large number of feedbacks and processes involved, determination of the cause of this correlation is not simple [*Stevens and Feingold*, 2009].

A strong link is also observed between τ and f_c in both observations [*Sekiguchi et al.*, 2003; *Kaufman et al.*, 2005; *Kaufman and Koren*, 2006; *Loeb and Schuster*, 2008; *Koren et al.*, 2008; *Dey et al.*, 2011; *Koren et al.*, 2010b; *Small et al.*, 2011] and models [*Myhre et al.*, 2007; *Quaas et al.*, 2009; *Grandey et al.*, 2013]. These correlations have been found in several different cloud regimes, such as stratocumulus [*Costantino and Bréon*, 2013] and convective anvils [*Koren et al.*, 2010b], but they all show the same general form, a strong increase in f_c with increasing τ. Some studies find a decrease in f_c at high τ in regions of strong aerosol absorption [e.g., *Koren et al.*, 2008], but a positive τ-f_c relationship is found in the majority of regions. A large fraction of the τ-f_c correlation is thought to be due to effects other than aerosol-cloud interactions such as cloud contamination of the aerosol retrieval [*Zhang et al.*, 2005], cloud 3-D effects [*Wen et al.*, 2007], aerosol humidification [*Twohy et al.*, 2009; *Quaas et al.*, 2010; *Chand et al.*, 2012; *Grandey et al.*, 2013] and other meteorological influences [*Engstrom and Ekman*, 2010]. Observational studies have limited the fraction of the total τ-f_c relationship due to aerosol effects as less than 70% [*Mauger and Norris*, 2007; *Engstrom and Ekman*, 2010] and less than 50% [*Gryspeerdt et al.*, 2014]. Studies using general circulation models (GCMs) suggest that the fraction of the τ-f_c relationship due to aerosol–cloud interactions is even smaller, although due to large uncertainties they do not provide numerical estimates [*Quaas et al.*, 2010; *Grandey et al.*, 2013].

These previous studies of the τ-p_{top} and τ-f_c correlations have shown strong correlations with many different observing systems, suggesting that retrieval errors or other measurement effects are not the primary cause of these correlations between aerosol and cloud properties. However, due to effects such as aerosol humidification, τ may not be a good proxy for CCN [e.g., *Nakajima et al.*, 2001].

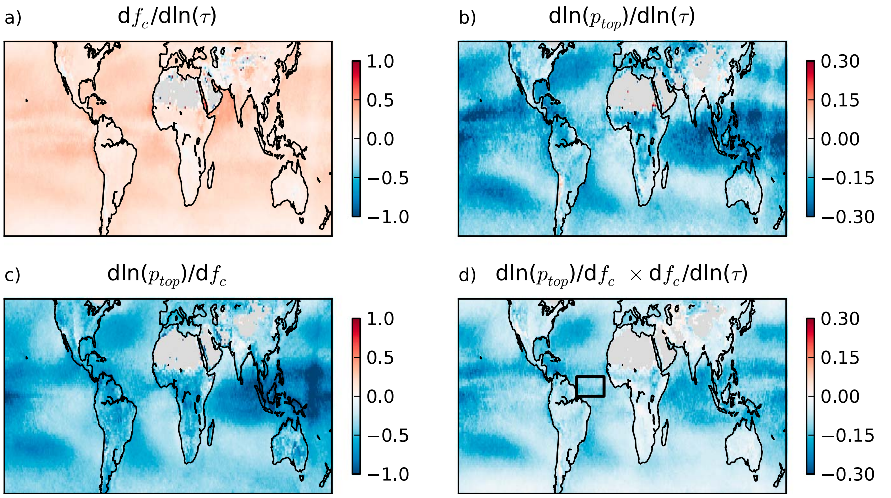

Figure 1. (a) Sensitivity of cloud fraction to ln(τ) (df_c/dln(τ)), (b) sensitivity of ln(p_{top}) to ln(τ), and (c) sensitivity of ln(p_{top}) to f_c. (d) The reconstructed ln(p_{top})-ln(τ) sensitivity generated assuming the relationship is mediated by f_c. The highlighted region in Figure 1d is studied further in Figure 2.

The influence of the τ-f_c correlation on the τ-p_{top} correlation has been previously noted by *Myhre et al.* [2007], but they did not demonstrate the extent to which the τ-f_c correlation could be influencing the τ-p_{top} relationship. Here we show how this strong τ-f_c relationship may explain the majority of the τ-p_{top} relationship across the globe. This underscores the importance of accounting for f_c when considering relationships between aerosol and cloud properties.

2. Method

We make use of 9 years (2003–2011) of Moderate Resolution Imaging Spectroradiometer (MODIS) Terra cloud [*Platnick et al.*, 2003] and aerosol [*Remer et al.*, 2005] daily level three data at 1° by 1° resolution for the region 50°N-50°S. We use the cloud top properties (MOD06_L2) cloud fraction retrieval as our cloud fraction product from the level 3 (MOD08_D3) data set, although these results are applicable when using other cloud fraction products. There is evidence of heavy aerosol being misclassified as cloud by the MODIS cloud retrieval [*Brennan et al.*, 2005; *Hubanks et al.*, 2008]. Restricting the maximum τ to 0.6 partially accounts for the influence of aerosols on the f_c retrieval, although not for cloud contamination of the aerosol retrieval. The aerosol retrieval used is the standard dark-target MODIS τ retrieval, "Optical Depth Land and Ocean Mean." As MODIS cannot make colocated observations of aerosol and cloud properties, we assume the level 3 τ is representative of the entire gridbox. Gridboxes with no τ retrieval are excluded from this analysis.

To investigate the strength of the relationships between ln(τ), f_c, and ln(p_{top}), we define the sensitivity as the slope of a linear regression between two quantities. To avoid errors from seasonal effects or climatological spatial gradients [*Grandey and Stier*, 2010], we calculate sensitivities locally, at 1° by 1° scale and separately for each season, combining the seasonal sensitivities using a standard-error weighted mean.

3. Results

Similar to previous studies, we find strong sensitivities of both f_c (Figure 1a) and p_{top} (Figure 1b) to τ over the majority of the globe. We also find a strong sensitivity of p_{top} to f_c (Figure 1c), especially in convective regions. This is likely due to deep convective systems having both a high f_c and low p_{top}; high clouds with a low f_c are much rarer in the MODIS L3 data than high clouds with a high f_c, whereas low f_c situations are much more common for clouds with low cloud tops. Although retrieval errors could generate a negative correlation between f_c and p_{top} for low clouds [*Zuidema et al.*, 2009], the existence of a strong sensitivity of cloud top height to τ when using radar/lidar [*Niu and Li*, 2012] suggests that p_{top} retrieval errors are not the primary cause of the f_c-p_{top} sensitivity observed here. While the changes in p_{top} may not be a result of changes in f_c, we can make use of this statistical relationship between the cloud properties.

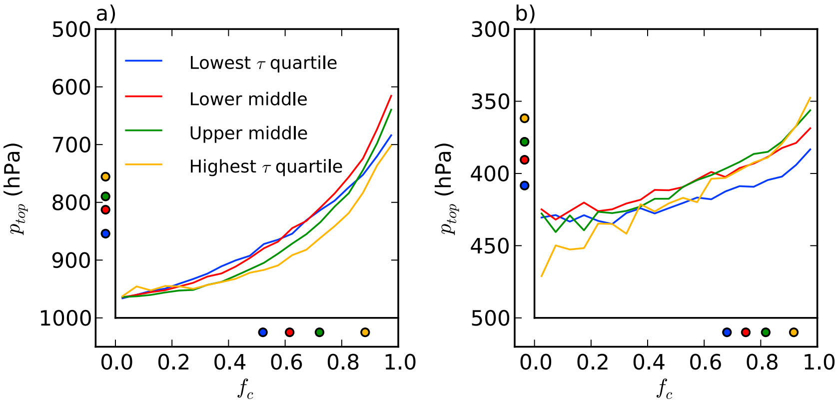

Figure 2. (a) The dependence of mean p_{top} on f_c for four τ quartiles. The dots on the axes indicate the mean of the property for each τ quartile. (b) Same as Figure 2a but restricting the p_{top} to those with a cloud top above 600 hPa (p_{top} less than 600 hPa).

Using the sensitivity of p_{top} to f_c and f_c to τ, the sensitivity of p_{top} to τ can be considered as in equation (1). The combination of the statistical relationships between f_c, p_{top}, and τ can then be used to determine the residual term, the part of the sensitivity of p_{top} to τ that is not mediated by f_c. The residual term includes the sensitivity of p_{top} to τ at constant f_c (and with constant meteorology) as well as other terms. Using the natural logarithm of the τ allows the use of linear regression to determine the sensitivities as the relationship between τ and cloud properties has been observed to be nonlinear.

$$\frac{\mathrm{dln}(p_{\mathrm{top}})}{\mathrm{dln}(\tau)} = \frac{\mathrm{dln}(p_{\mathrm{top}})}{\mathrm{d}f_c} \times \frac{\mathrm{d}f_c}{\mathrm{dln}(\tau)} + \mathrm{Residual} \tag{1}$$

When the negative relationship between f_c and p_{top} in Figure 1c is multiplied by the strong positive sensitivity of f_c to τ (as in equation (1)), we can generate a pattern between τ and p_{top} (Figure 1d) that is similar to that found when calculating the sensitivity of p_{top} to τ (Figure 1b). Although the sensitivity of p_{top} to f_c is likely the result of synoptic effects in the clouds, the sensitivity of f_c to τ is largely due to effects other than an aerosol influence on cloud fraction, such as retrieval errors and meteorological covariations [*Quaas et al.*, 2010; *Grandey et al.*, 2013]. The dependence of the τ-p_{top} sensitivity on the τ-f_c sensitivity suggests that meteorological covariations and retrieval errors also exert a strong influence on the strength of the τ-p_{top} sensitivity.

A closer examination of clouds in the central tropical Atlantic (10°N-0°S,20°W-50°W)(the region marked in Figure 1d, similar to that used in *Koren et al.* [2010b]) shows the relationship between f_c and p_{top} has a weak dependence on τ (Figure 2a). This region has many convective clouds and is also in the outflow region for African aerosol, providing a good location for the study of potential aerosol influences on p_{top}.

For a given f_c, the higher τ populations have typically lower cloud tops (a higher p_{top}). Given the prevalence of low clouds, and the difficulty in retrieving the p_{top} for these clouds, it is possible that this negative relationship is due to the retrieval rather than an effect of aerosols on cloud properties. This dependence is opposite from that seen with the mean p_{top} (dots in Figure 2a), where increased τ is correlated with a decrease in p_{top}. We find a strong τ-f_c relationship in this region, which when combined with the strong f_c-p_{top} relationship, results in an decrease in p_{top} at increased τ despite the τ-p_{top} relationship having the opposite sign at fixed f_c in this region.

As the convective invigoration hypothesis predicts effects mainly on high topped cloud, we also repeat this analysis restricting the p_{top} retrievals to only those with cloud tops above 600 hPa (p_{top} less than 600 hPa) (Figure 2b). The mean p_{top} for retrievals above 600 hPa is determined using the p_{top} histogram in the level 3 MODIS product. This has the added benefit of being in the altitude region where MODIS determines p_{top} using CO_2 slicing rather than IR temperatures, resulting in a more accurate determination of the p_{top} [*Menzel et al.*, 2008]. For these high clouds, p_{top} is not such a strong function of f_c. There is also a weak dependence of p_{top} on τ for fixed f_c, displaying higher clouds at higher τ. However, the combination of the τ-f_c and the p_{top}-f_c relationships are still acting to increase the observed τ-p_{top} relationship.

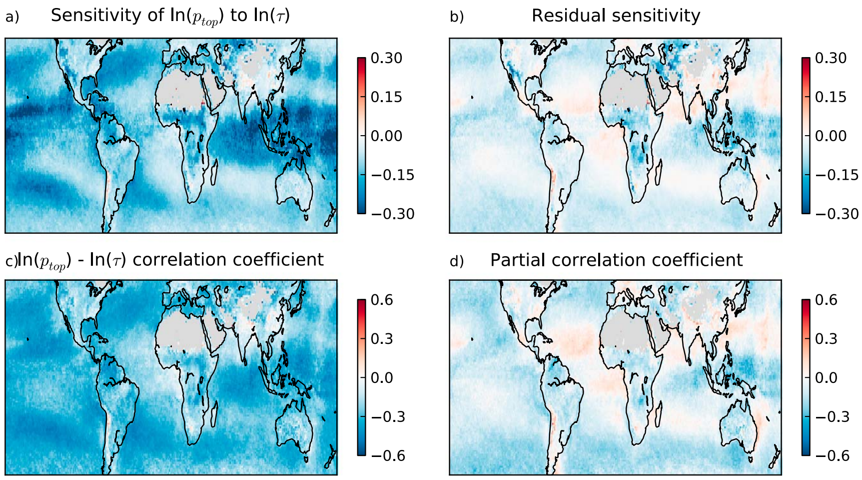

Figure 3. (a) The sensitivity of ln(p_{top}) to ln(τ) over 9 years of MODIS data (as in Figure 1b). (b) The residual sensitivity of ln(p_{top}) to ln(τ) once the reconstructed τ-p_{top} relationship (equation (1)) is removed. (c) The correlation of ln(p_{top}) and ln(τ). (d) The partial correlation (equation (2)) of ln(p_{top}) to ln(τ) accounting for f_c as the covarying variable.

The strength of the τ-f_c correlation and its ability to generate a strong relationship between p_{top} and τ then leads us to question what proportion of the τ-p_{top} relationship is not attributable to the τ-f_c relationship (in this framework) and thus may be due to an aerosol influence on cloud properties.

We show the sensitivity of ln(p_{top}) to ln(τ) in Figure 3a. If we assume that the dependence of the f_c-p_{top} relationship on τ is small, we can subtract the "reconstructed" relationship from Figure 1d, to leave the residual sensitivity (Figure 3b). The mean residual sensitivity is much smaller than the total sensitivity, in some regions becoming positive, indicating an increase in p_{top} (decrease in cloud top height) with increasing τ. These decreases in height are located in regions with large amounts of low-lying cloud, indicating that low stratiform cloud may not respond to aerosol perturbations in the same way as convective clouds. Not all of the regions with large amounts of low-level cloud show this positive sensitivity, with the West Coast of South America showing a negative residual sensitivity, compared to the positive residual sensitivity found in some parts of the Atlantic and the northwest Pacific. Regions where absorbing aerosol is more common, such as the southeast Atlantic and North Indian Ocean show a reduction in cloud top height with increasing τ. This may indicate the possibility of a semidirect effect [e.g., *Koren et al.*, 2008; *Koch and Del Genio*, 2010] in regions where low clouds are common, as only the (relatively) clean West Pacific shows a negative sensitivity.

There is also a possibility of meteorological covariation generating the observed relationship. We have not explicitly accounted for meteorological covariations here, and although the removal of the f_c influence on the τ-p_{top} sensitivity accounts for some (due to the large influence of meteorology on the τ-f_c correlation), it is likely that they are still important in the residual sensitivity.

We also examine the correlation between ln(p_{top}) and ln(τ) (Figure 3c). We find a strong negative correlation over the majority of the tropics, with a decrease in the strength of the correlation on the eastern edge of the Atlantic Ocean. To account for the effect of f_c as a controlling variable, we compute the residual correlation coefficient by using the partial correlation coefficient [*Hazewinkel*, 2002]. The partial correlation (equation (2)) is designed to measure the linear dependence of one variable (p_{top}) on another (τ), with the effect of the controlling variable (f_c) removed. The correlation coefficient between variables x and y is r_{x-y}.

$$r_{p_{\mathrm{top}}-\tau\cdot f_c} = \frac{r_{p_{\mathrm{top}}-\tau} - r_{p_{\mathrm{top}}-f_c} r_{f_c-\tau}}{\sqrt{1 - r^2_{p_{\mathrm{top}}-f_c}}\sqrt{1 - r^2_{f_c-\tau}}} \tag{2}$$

The partial correlation (Figure 3d) displays a similar pattern to the residual sensitivity. There is a negative correlation over the majority of the globe; however, in certain regions there is a positive correlation between p_{top} and τ, indicating a reduction in cloud height with increasing τ. These regions are characterized by stratocumulus clouds, which would not be expected to respond vertically to aerosol perturbations.

4. Discussion and Conclusions

The results suggest that a large part of the satellite-retrieved τ-p_{top} relationship is an a consequence of the strong τ-f_c sensitivity. As in previous work, we have observed strong ln(τ)-ln(p_{top}) and ln(τ)-f_c correlations globally. We note that there is also a strong f_c-ln(p_{top}) correlation. When the ln(τ)-f_c sensitivity is multiplied by the sensitivity of f_c to ln(p_{top}), we find a similar pattern and magnitude to the sensitivity of ln(p_{top}) to ln(τ). Calculating a residual ln(τ)-ln(p_{top}) sensitivity, we find that in some cases ln(τ) is positively correlated with decreases in cloud height (increases in p_{top}), an effect that is obscured when f_c variations are not considered.

A large part of the τ-f_c correlation has been suggested to be due to effects other than aerosol-cloud interactions, such as meteorological covariation [*Quaas et al.*, 2010]. This in turn suggests that the residual ln(τ)-ln(p_{top}) sensitivity and correlation might be closer to the true effect of aerosols on p_{top}. There are two major caveats to the calculation of this residual. The first is that it is likely that there are other meteorological effects which could generate the observed τ-p_{top} correlation. Accounting for these would likely reduce the residual sensitivity and correlation further.

Second, we have ignored the potential effect of aerosols on f_c. Aerosols may be able to influence the transition between closed and open-celled stratocumulus, increasing f_c [*Rosenfeld et al.*, 2006]. An aerosol influence on f_c could, through the p_{top}-f_c relationship, produce a τ-p_{top} relationship. This would act to increase the residual sensitivity and the residual correlation. However, the proportion of the τ-f_c relationship that is due to the effect of aerosol on f_c is thought to be small. Observational estimates restrict the sensitivity to less than half of the total sensitivity shown in Figure 1a [*Mauger and Norris*, 2007; *Gryspeerdt et al.*, 2014], while GCM-based studies suggest that the aerosol-induced fraction of the τ-f_c relationship is much smaller. We do not include a numerical estimate of the effect on the τ-p_{top} sensitivity due to the large uncertainties involved.

Not all studies will be affected by the τ-f_c correlation, for example, studies that do not use τ to define high and low aerosol [e.g., *Yuan et al.*, 2011] are likely immune from this issue. Studies that investigate cloud development [e.g., *Gryspeerdt et al.*, 2014] can also account for the τ-f_c relationship while still being able to investigate the aerosol influence on f_c.

In this work, we have shown that a significant fraction of the observed relationship between τ and p_{top} can be attributed to influences on the τ-f_c relationship from effects other than aerosol-cloud interactions. This disguises the magnitude and in some cases the sign of the relationship between τ and p_{top}. The influence of the τ-f_c sensitivity does not account for the entire ln(τ)-ln(p_{top}) relationship, the residual sensitivity still shows a small negative sensitivity of p_{top} to τ in convective regions. In regions where low-lying stratiform clouds are common, the residual ln(τ)-ln(p_{top}) sensitivity is positive, perhaps indicating a different response of these regimes to increases aerosol. This study demonstrates that the strength of the τ-f_c sensitivity has a strong influence on the sensitivity of other cloud properties to τ. This emphasizes the importance of accounting for the τ-f_c correlation and the associated meteorological covariations when investigating aerosol-cloud interactions.

Acknowledgments
The MODIS data used in this work were obtained from the NASA Goddard Space Flight Center. E. Gryspeerdt was supported by a UK Natural Environment Research Council (NERC) studentship. The research leading to this work has received funding from the European Research Council under the European Union's Seventh Framework Programme (FP7/2007-2013) / ERC grant agreement FP7-280025. B.S. Grandey was funded by the Singapore National Research Foundation (NRF) through the Singapore-MIT Alliance for Research and Technology (SMART) Center for Environmental Sensing and Modeling (CENSAM).

The Editor thanks two anonymous reviewers for their assistance in evaluating this paper.

References

Brennan, J., Y. Kaufman, I. Koren, and R. Li (2005), Aerosol cloud interaction—Misclassification of MODIS clouds in heavy aerosol, *IEEE Trans. Geosci. Remote*, *43*, 911–915, doi:10.1109/TGRS.2005.844662.

Chand, D., R. Wood, S. J. Ghan, M. Wang, M. Ovchinnikov, P. J. Rasch, S. Miller, B. Schichtel, and T. Moore (2012), Aerosol optical depth increase in partly cloudy conditions, *J. Geophys. Res.*, *117*, D17207, doi:10.1029/2012JD017894.

Costantino, L., and F.-M. Bréon (2013), Aerosol indirect effect on warm clouds over south-east Atlantic, from co-located MODIS and CALIPSO observations, *Atmos. Chem. Phys.*, *13*, 69–88, doi:10.5194/acp-13-69-2013.

Dey, S., G. L. Di, G. Zhao, A. L. Jones, and G. M. McFarquhar (2011), Satellite-observed relationships between aerosol and trade-wind cumulus cloud properties over the Indian Ocean, *Geophys. Res. Lett.*, *38*, L01804, doi:10.1029/2010GL045588.

Engstrom, A., and A. M. Ekman (2010), Impact of meteorological factors on the correlation between aerosol optical depth and cloud fraction, *Geophys. Res. Lett.*, *37*, L18814, doi:10.1029/2010GL044361.

Grandey, B., and P. Stier (2010), A critical look at spatial scale choices in satellite-based aerosol indirect effect studies, *Atmos. Chem. Phys.*, *10*, 11,459–11,470, doi:10.5194/acp-10-11459-2010.

Grandey, B. S., P. Stier, and T. M. Wagner (2013), Investigating relationships between aerosol optical depth and cloud fraction using satellite, aerosol reanalysis and general circulation model data, *Atmos. Chem. Phys.*, *13*, 3177–3184, doi:10.5194/acp-13-3177-2013.

Gryspeerdt, E., P. Stier, and D. G. Partridge (2014), Satellite observations of cloud regime development: The role of aerosol processes, *Atmos. Chem. Phys.*, *14*, 1141–1158, doi:10.5194/acpd-13-22931-2013.

Hazewinkel, M. (Ed.) (2002), *Encyclopedia of Mathematics*, Springer, New York.

Hubanks, P. A., M. D. King, S. A. Platnick, and R. A. Pincus (2008), Modis atmosphere L3 gridded product algorithm theoretical basis, *Tech. Rep. ATBD-MOD-30*, National Aeronautics and Space Administration.

Kaufman, Y., I. Koren, L. Remer, D. Rosenfeld, and Y. Rudich (2005), The effect of smoke, dust, and pollution aerosol on shallow cloud development over the Atlantic Ocean, *Proc. Nat. Acad. Sci. U S A*, *102*(32), 11,207–11,212, doi:10.1073/pnas.0505191102.

Kaufman, Y. J., and I. Koren (2006), Smoke and pollution aerosol effect on cloud cover, *Science*, *313*, 655–658, doi:10.1126/science.1126232.

Koch, D., and A. D. Del Genio (2010), Black carbon semi-direct effects on cloud cover: Review and synthesis, *Atmos. Chem. Phys.*, *10*, 7685–7696, doi:10.5194/acp-10-7685-2010.

Koren, I., Y. Kaufman, D. Rosenfeld, L. Remer, and Y. Rudich (2005), Aerosol invigoration and restructuring of Atlantic convective clouds, *Geophys. Res. Lett.*, *32*, L14828, doi:10.1029/2005GL023187.

Koren, I., J. Martins, L. A. Remer, and H. Afargan (2008), Smoke invigoration versus inhibition of clouds over the Amazon, *Science*, *321*, 946–949, doi:10.1126/science.1159185.

Koren, I., L. Remer, O. Altaratz, J. Martins, and A. Davidi (2010a), Aerosol-induced changes of convective cloud anvils produce strong climate warming, *Atmos. Chem. Phys.*, *10*, 5001–5010, doi:10.5194/acp-10-5001-2010.

Koren, I., G. Feingold, and L. Remer (2010b), The invigoration of deep convective clouds over the Atlantic: Aerosol effect, meteorology or retrieval artifact?, *Atmos. Chem. Phys.*, *10*, 8855–8872, doi:10.5194/acp-10-8855-2010.

Loeb, N. G., and G. L. Schuster (2008), An observational study of the relationship between cloud, aerosol and meteorology in broken low-level cloud conditions, *J. Geophys. Res.*, *113*, D14214, doi:10.1029/2007JD009763.

Mauger, G., and J. Norris (2007), Meteorological bias in satellite estimates of aerosol-cloud relationships, *Geophys. Res. Lett.*, *34*, L16824, doi:10.1029/2007GL029952.

Menzel, W., et al. (2008), MODIS global cloud-top pressure and amount estimation: Algorithm description and results, *J. Appl. Meteorol. Clim.*, *47*, 1175–1198, doi:10.1175/2007JAMC1705.1.

Myhre, G., et al. (2007), Aerosol-cloud interaction inferred from MODIS satellite data and global aerosol models, *Atmos. Chem. Phys.*, *7*, 3081–3101, doi:10.5194/acp-7-3081-2007.

Nakajima, T., A. Higurashi, K. Kawamoto, and J. Penner (2001), A possible correlation between satellite-derived cloud and aerosol microphysical parameters, *Geophys. Res. Lett.*, *28*, 1171–1174, doi:10.1029/2000GL012186.

Niu, F., and Z. Li (2012), Systematic variations of cloud top temperature and precipitation rate with aerosols over the global tropics, *Atmos. Chem. Phys.*, *12*, 8491–8498, doi:10.5194/acp-12-8491-2012.

Platnick, S., M. King, S. Ackerman, W. Menzel, B. Baum, J. Riedi, and R. Frey (2003), The MODIS cloud products: Algorithms and examples from Terra, *IEEE Trans. Geosci. Remote*, *41*, 459–473, doi:10.1109/TGRS.2002.808301.

Quaas, J., et al. (2009), Aerosol indirect effects—General circulation model intercomparison and evaluation with satellite data, *Atmos. Chem. Phys.*, *9*, 8697–8717, doi:10.5194/acp-9-8697-2009.

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*, 6129–6135, doi:10.5194/acp-10-6129-2010.

Remer, L., et al. (2005), The MODIS aerosol algorithm, products, and validation, *J. Atmos. Sci.*, *62*, 947–973, doi:10.1175/JAS3385.1.

Rosenfeld, D., Y. J. Kaufman, and I. Koren (2006), Switching cloud cover and dynamical regimes from open to closed Benard cells in response to the suppression of precipitation by aerosols, *Atmos. Chem. Phys.*, *6*, 2503–2511, doi:10.5194/acp-6-2503-2006.

Rosenfeld, D., U. Lohmann, G. Raga, C. O'Dowd, M. Kulmala, S. Fuzzi, A. Reissell, and M. Andreae (2008), Flood or drought: How do aerosols affect precipitation?, *Science*, *321*, 1309–1313, doi:10.1126/science.1160606.

Sekiguchi, M., T. Nakajima, K. Suzuki, K. Kawamoto, A. Higurashi, D. Rosenfeld, I. Sano, and S. Mukai (2003), A study of the direct and indirect effects of aerosols using global satellite data sets of aerosol and cloud parameters, *J. Geophys. Res.*, *108*(D22), 4699, doi:10.1029/2002JD003359.

Small, J. D., J. H. Jiang, H. Su, and C. Zhai (2011), Relationship between aerosol and cloud fraction over Australia, *Geophys. Res. Lett.*, *38*, L23802, doi:10.1029/2011GL049404.

Stevens, B., and G. Feingold (2009), Untangling aerosol effects on clouds and precipitation in a buffered system, *Nature*, *461*, 607–613, doi:10.1038/nature08281.

Twohy, C., J. Coakley, and W. Tahnk (2009), Effect of changes in relative humidity on aerosol scattering near clouds, *J. Geophys. Res.*, *114*, D05205, doi:10.1029/2008JD010991.

Wen, G., A. Marshak, R. Cahalan, L. Remer, and R. Kleidman (2007), 3-D aerosol-cloud radiative interaction observed in collocated MODIS and ASTER images of cumulus cloud fields, *J. Geophys. Res.*, *112*, D13204, doi:10.1029/2006JD008267.

Williams, E., et al. (2002), Contrasting convective regimes over the Amazon: Implications for cloud electrification, *J. Geophys. Res.*, *107*(D20), 8082, doi:10.1029/2001JD000380.

Yuan, T., L. Remer, and H. Yu (2011), Microphysical, macrophysical and radiative signatures of volcanic aerosols in trade wind cumulus observed by the A-train, *Atmos. Chem. Phys.*, *11*, 7119–7132, doi:10.5194/acp-11-7119-2011.

Zhang, J., J. Reid, and B. Holben (2005), An analysis of potential cloud artifacts in MODIS over ocean aerosol optical thickness products, *Geophys. Res. Lett.*, *32*, L15803, doi:10.1029/2005GL023254.

Zuidema, P., D. Painemal, S. de Szoke, and C. Fairall (2009), Stratocumulus cloud-top height estimates and their climatic implications, *J. Clim.*, *22*, 4652–4666, doi:10.1175/2009JCLI2708.1.