**Atmospheric
Chemistry
and Physics
Discussions**

Interactive comment on "Investigating relationships between aerosol optical depth and cloud fraction using satellite, aerosol reanalysis and general circulation model data" *by* B. S. Grandey et al.

B. S. Grandey et al.

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We would like to thank both referees for their thoughtful reviews. We have made changes following their comments, improving the quality of the manuscript. Below, we respond to each reviewer's comments (italicised) in turn before providing a summary of the changes we have made to the manuscript.

Response to Referee 1

This study reports on relationships between AOD and cloud fraction using a variety of tools with the goal to identify factors controlling these relationships. The study makes use of satellite data and modeling and follows upon previous work of somewhat similar nature by the authors. The topic of this manuscript is of high interest to this journal and addresses a critically important issue, specifically the effect of errors and actual processes on aerosol-cloud fraction relationships. The manuscript discusses the relative roles of several factors (retrieval/model errors, wet scavenging, cloud lifetime effect, and aerosol swelling via hygroscopic uptake). Many important results are presented, including that positive AOD-cloud fraction relationships are more due to aerosol swelling rather than lifetime effects (in the ECHAM5-HAM Model). Also, wet scavenging may lead to negative relationships in the tropics. The methodology is of high quality, the paper is concise and written well, and the conclusions are well-supported by the analysis. I support publication of this work but would like to ask the authors to at least discuss the parameter "aerosol index (AI)", which is ignored in favor of aerosol optical depth. Many studies have shown that AI may be a better parameter to represent CCN concentration than AOD; therefore, using AI may be more meaningful in a study of this nature as it accounts for the size distribution of aerosol to some degree. The authors should address this issue in light of what recent literature suggests regarding AI's benefits over AOD.

Thank you for the summary, and for suggesting that we discuss AI. We have now added a discussion about AI at the end of the 'Results and discussion' section.

Response to Referee 2

General comments:

The research presented here explores the relationship between cloud fraction (fc) and aerosol optical depth using multiple datasets to determine the causes for the persistent positive slopes derived using satellite data. This is an intriguing problem that points to the challenges inherent in remote sensing applications and in the implications of using this data for understanding the climate response to anthropogenic aerosol. The potential mechanisms of the positive relationships are listed clearly, and different tools and methods are applied to investigate these possibilities. A novel approach is used to examine this response, however, statistical rigor and an assessment of the uncertainty with the fc-tau relationship derived from space and its comparison to the models is lacking. It remains unclear under what conditions can the satellite retrievals be trusted and, what options do the users have in reducing the biases (of the satellite data) described here. This paper could be a useful guide to the many scientists who use satellite retrievals to investigate aerosol indirect effects. With additional statistical tests and clarification, this paper would be suitable for publication.

It has been suggested (e.g., Penner et al., 2011, PNAS) that AI (Aerosol Index, or the optical depth times angstrom exponent) is a better proxy of cloud drop number concentration than AOD as the estimated aerosol indirect forcing using AI are closer to the values predicted by the model. Thus it would be beneficial to apply AI to discuss how it would affect the results, as also indicated by Referee 1.

Thank you for your summary and suggestions. As mentioned in the response to Referee 1, we have now added a discussion about AI at the end of the 'Results and discussion' section. Following your recommendation to include more statistical tests, we have now included information about the size of the standard errors in the Figure 1 and Figure 2 captions. For those interest in the slopes, the colouring in Figure S3 communicates the result of statistical significance tests – we have added this to the

updated caption, a clarification we had accidentally omitted previously.

Specific points: Pg 30806 L10: What is meant by residual?

We have now deleted this word here, in order to avoid confusion.

Pg 30806 L13: Isn't wet scavenging also an important process in the mid-latitudes?

We have now clarified that we look only at scavenging due to 'convective' precipitation (which dominates in the tropics). Thank you for highlighting this potential misunderstanding.

Pg 30806 L14 – 17: Explain why wet scavenging events are "likely" poorly sampled in satellite data? I can name several instruments that have the capacity to accurately measure precipitation, such as CloudSat, TRIMM, AMSR-E, to name a few.

Thank you for raising this. We have now explained that this poor sampling is "because the properties of aerosol below clouds cannot be retrieved".

Abstract: The main point of this paper is aiming to understand the fc-tau relationship and all of the factors that influence the response. Is it possible to include an uncertainty or error assessment on this relationship and include this in the abstract? Such as, the average slopes (and errors on the slopes) of the Fc-tau relationships derived using each method.

Thank you for these suggestions. We have now included mention of the area-weighted mean results of approximately 0.2 (Aqua-MODIS) and 0.1 (MODIS-MACC) in the abstract. We do not include the means for the model results, because the sign changes are of more importance. For information on statistical tests, please see our response to you general comments above.

Pg 30807, L2: The assumption that cloud coverage increases with aerosol is not a very good assumption. Increasing aerosol concentrations can also decrease cloud coverage via the "semi- direct effect" through absorbing aerosol (Ackerman et al., 2000;

Wilcox 2010, ACP), through increasing giant cloud condensation nuclei (Feingold et al., 1999, JAS), and negative responses (such as lower liquid water path and cloud albedo) have also been observed in ship tracks (e.g., Christensen et al., 2012, JGR; Chen et al., 2012, ACP). For completeness, these aspects about the general science should be incorporated into the discussion.

Thank you for pointing this out. We now briefly mention the possibility that aerosol may decrease cloud cover and of the semi-direct effect in the third point in the introduction. However, we still focus slightly more on the positive cloud lifetime effect because it is this effect which has often been used to interpret the positive f_c–τ relationships in satellite data.

Pg 30807, L6-7: define "large regional scales"

We have now done this, mentioning regions larger than $4° \times 4°$.

Pg 30807, L22-24: Explain how cloud processing affects the optical properties of the aerosol? The point of this sentence in relating the slope of fc-tau is not clear.

Thank you for this suggestion. We have added further discussion, including two further references, to the seventh point of the introduction in order to explain this.

Pg 30807, L25: the word "additional" is unclear. How many tools prior to this are being used?

We have deleted "additional" in order to avoid ambiguity.

Pg 30809, L6, Are points 1 and 7 being explored? If not, explain why. This aspect is mentioned again in L3-4 of pg 30814. Why are these not tested in the paper?

Thank you for questioning this. We have added further discussion and clarification to the manuscript. (Please see summary of changes below.)

Pg 30811, L20 – 26: 'a surface albedo of 0'. It is not a very good assumption. This "back of the envelope calculation" would be more insightful if a more representative

surface albedo was used, I would suggest a value closer to 0.1. Also, please clarify that increasing the cloudiness, "increases" the upwelling shortwave radiation at the top of the atmosphere, not "decreases" it! In addition, more clouds are going to "decrease" outgoing longwave radiation at the top of the atmosphere. Perhaps the authors are referring to the changes at the surface, if so, please correct the terminology.

Thank you for suggesting a more realistic ocean albedo and for the correction about the TOA radiation. We have adopted both of your suggestions.

Pg 30812 L1-3: CERES does not measure low-level cloudiness, it actually ingests MODIS cloud data to infer cloud coverage over the relatively large CERES footprint of 20 km. What information from CERES was actually used in this study to derive the fc-tau relationships? And please explain why the relationship was presumably weaker in the CERES/globAerosol product compared to MODIS derived fc-tau. Was it an artifact of the retrieval? Resolution, instrument sensitivity, differences, please explain, if this dataset is to be discussed in the paper.

The CERES Single Scanner Footprint dataset actually uses MODIS data: Collection 4 aerosol is combined with an independent CERES team cloud retrieval. Thank you for suggesting that we include further discussion here. However, we think that discussion of these datasets and detailed discussion of the corresponding f_c–τ relationships is outside the scope of this paper, which focuses on MODIS as the satellite dataset. The CERES and AATSR results do not form an important part of the flow of this paper; they are merely mentioned to show that the positive f_c–τ relationships are not unique to MODIS. Interested readers are referred to Chapter 3 of Grandey (2011), which is easily accessible online at the citable URL provided in the References section.

Pg 30813 line 29: relativity humidity -> relative humidity.

Thank you. This has now been corrected.

Pg 30816 L12: I would add the word "aerosol optical depth" after the words "low and

high.”

Thank you. We have added τ.

Pg 30816 L18: It has been commented concerning the possible model errors and bias. What kind of retrieval errors are being referred to here? Is it the "residual" cloud contamination aerosol retrieval? It would be useful if the model uncertainties and bias analysis can be provided and discussed.

Thank you for these suggestions. We have changed "retrieval errors" to "cloud contamination" in order to be more specific. We have also now mentioned in the Method section that the MACC data are designed to be unbiased with respect to MODIS τ data.

Summary of changes to revised manuscript

30806.5 - Added "A global mean f_c increase of approximately 0.2 between low and high τ conditions is found for both ocean and land."

30806.10 - Deleted "residual".

30806.11 - Added "The global mean f_c increase between low and high τ conditions is reduced to 0.1, suggesting that cloud contamination may account for approximately one half of the satellite-retrieved increase in f_c."

30806.14 - added "convective" before "precipitation".

30806.15 - Added "because the properties of aerosol below clouds cannot be retrieved".

30806.25 - Added "However, increasing aerosol concentrations also have the potential decrease cloud fractional cover, for example via the semi-direct effect (ackerman et al., 2000).

30807.7 - Added "larger than $4° \times 4°$."

30808.24 - Added "Aerosol which has been recently cycled through a cloud may be more hydrated than aerosol further away, potentially leading to an increase in τ in the immediate vicinity of clouds (Koren et al., 2007). However, the relative humidity fluctuations produced by clouds are localised, extending to less than 500 m from the cloud edge (Bar-Or et al., 2012). Therefore it is unlikely that this localised effect could drive significant f_c–τ relationships on scales larger than a few kilometres. (It is worth noting that this effect, whereby clouds may affect aerosol properties, is different from the larger scale relative humidity effect, discussed in the fourth point above, whereby relative humidity variations drive cloud formation.)"

30808.25 - Deleted "additional".

30809.3 - Added "Spatial gradient effects (first point above) have been investigated

elsewhere and are accounted for in the methodology used in this paper (Grandey and Stier, 2012). As discussed in the seventh point above, cloud processing effects are unlikely to significantly contribute to f_c–τ relationships or scales larger than a few kilometres, so cloud processing is not investigated here. Apart from relative humidity, other meteorological factors (fifth point above) are outside the scope of the current paper, remaining an important topic for further research."

30809.19 - Added "The MACC data are designed to be unbiased with respect to MODIS τ data (Morcrette et al., 2011)."

30811.21 - Changed ocean albedo to 0.1. (Note: result unchanged.)

30811.24 - "a shortwave radiation decrease" -> "an upwelling shortwave radiation increase",

30811.25 - "sortwave increase" -> "shortwave decrease"; "longwave increase" -> "longwave decrease".

30813.28 - "relativity" -> "relative".

30816.9 - Added "In this paper, τ has been used, following the observational studies of Koren et al. (2005), Kaufman et al. (2005) and Yuan et al. (2011). However, it has been suggested that aerosol index (AI), the product of τ and the Ångström exponent, may provide a better measure of aerosol number burden than τdoes (Nakajima et al., 2001). This is because the size of the aerosol particles is taken into account via the Ångström exponent. As a result, some cloud–aerosol interaction studies have used AI instead of τ (e.g. Penner et al., 2011). It is unclear whether the findings presented here for f_c–τ relationships would also apply to f_c–AI relationships. It is possible that AI may be less affected by relative humidity than τ is, due to the fact that AI is less sensitive to aerosol size."

30816.12 - Added "τ".

30816.18 - "retrieval errors" -> "cloud contamination".

<div align="center">C13218</div>

30818.10 - Added Ackerman et al. (2000) reference.

30818.15 - Added Bar-Or et al. (2012) reference.

30819.13 - "in preparation" -> "submitted"; 2012 -> 2013.

30819.26 - Added Koren et al. (2007) reference.

30821.15 - Dropped "Atmos. Chem. Phys. Discuss."; 2012 -> 2013.

Figure 1 caption - Added "For more than 99% of the grid boxes with data, the mean difference is greater than the standard error in the mean difference for that grid box. The mean of the standard errors is 0.02."

Figure 2 caption - Added "The means of the standard errors are (a)–(c) 0.02 and (d)–(e) 0.03."

Supplementary material Figure S3 and S4 - Added Aqua-MODIS figs for completeness.

Supplementary material Figure S3 caption - Added "White regions are where the data are not significantly different from zero at two-sigma confidence."

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