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Atmospheric Chemistry and Physics Discussions

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Interactive Comment

Interactive comment on "Interpreting the cloud cover – aerosol optical depth relationship found in satellite data using a general circulation model" *by* J. Quaas et al.

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We thank the reviewer for her or his assessment of our study. The critics have helped us indeed to reformulate our manuscript in a way that the main results come out more clearly.

General comments:
This work investigates the feasibility of several hypotheses used to explain observed increases in aerosol optical depth (AOD) around cloudy regions to better understand the legitimacy of satellite measurements of this relationship. This is done utilizing

a General Circulation Model (ECHAM5). Generally speaking, the authors are attempting to address very relevant and important questions about the measurement of interactions between aerosols and clouds. Although utilizing a GCM to answer these questions allows for the completion of global simulations, allowing analysis of the relationships in question across a similar scale of conditions represented by the satellite data set, I'm not convinced that the GCM is actually able to capture the hypotheses investigated. More specifically, I have concerns about using a GCM to look at processes occurring at scales that are not well represented within the model grid box. I suppose that there is some information on these types of processes that can be accessed via statistical analysis, but I would require that the authors provide significantly more detail into some of their methods, and further explanation on how they are interpreting GCM results at a relatively coarse resolution at the cloud scale. As indicated by the comments below, I fear that the authors are not using appropriate tools in this evaluation, and without significant additional work, their conclusions are not justified or useful.

We partially agree with the reviewer. The GCM does not resolve many of the processes relevant to the relationship between cloud cover and AOD (a discussion of our thoughts on this can be found, e.g., in a recent paper of our second author in Stevens and Feingold, Nature 2009). If the question was to completely understand and quantify how cloud cover varies with varying aerosol concentration, different tools such as cloud-resolving models including detailed aerosol chemistry and physics would be needed. To date, however, such tools would not allow to analyse at the pertinent scale processes leading to the positive relationship between cloud cover and AOD found in satellite data due to limited computer capacities. Thus, we argue, that while the GCM as a tool is far from perfect, it allows us to analyse causes for the positive relationship between TCC and AOD at a large scale to a first order – at least given our result that resolved-scale processes turn out to be the most important contributors to this relationship in the GCMs. We added a paragraph detailing this to our manuscript, and revised abstract and conclusion in a way to convey this result much more clearly.

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Specific Comments:

Regarding evaluation of each of the listed hypotheses:

Hypothesis 1: How confident are you in the model's representation of the first aerosol indirect effect? Can you provide error estimates? If not, can you justify your use of this model to evaluate the relative contribution of the AIE to the AOD-TCC relationship? Since climate models are not necessarily known for their ability to accurately represent the transition from cloud to precipitation, and since this transition would largely impact cloud lifetime, can you provide an error analysis of the model's ability to do so?

We think that when analysing the TCC-AOD relationship, the first aerosol indirect effect (the influence of increased cloud condensation nuclei on cloud albedo at constant liquid water content) is of only minor importance. Concerning the second aerosol indirect effect, we acknowledge in our manuscript (p26019, l18) that the parameterisation in the model in terms of autoconversion is crude. However, the main result is to show that the second indirect effect is only of second order compared to the aerosol swelling effect. In our revised version of the manuscript, we made this point even clearer.

Hypothesis 2: I think that the convergence of aerosol could be captured in the model, but the accurate placement of clouds along meteorological features (frontal zones, gust fronts, etc.) may be a stretch. How confident are you in the model's ability to put clouds in the right place for meso and synoptic scale events? If not confident, can you explain your use of the model in evaluating this scenario?

If we understand correctly, what is in question here is the ability of the model to simulate motions leading to co-variation of aerosol concentrations and cloud cover at the resolved scale (correlations are done at the scale of the GCM grid-boxes). The cloud cover scheme diagnoses clouds whenever a part of the grid-cell becomes supersaturated, and this scheme as well as the model's ability to simulate large-scale

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motions have been evaluated elsewhere (e.g., Tompkins, J. Atmos. Sci. 2002; Pincus et al., J. Geophys. Res. 2008; Reichler and Kim, Bull. Am. Meteorol. Soc., 2008). We added some more detailed explanation as well as references referring to the studies evaluating the model to the revised manuscript, and would like to thank the reviewer helping us making the manuscript indeed much clearer and better to understand in these regards.

Hypothesis 3: Although the model can likely predict aerosol swelling in grid boxes with increased vapor via simple humidity curves, I don't believe that it can accurately represent the fine scale gradient that occurs between clear and cloudy air, and it is this gradient that would result in dramatic increases in AOD near cloud edges. I've included a real observation of this type of swelling at the edge of a cloud as seen by a high spectral resolution lidar. Note how small the difference is until right at cloud edge!
We agree with the reviewer. The fact that humidity fluctuations other than distinguishing between cloudy (saturated) and clear (sub-saturated) are neglected when computing clear-sky aerosol swelling likely underestimates the swelling in the vicinity of clouds. However, this would lead to an under-estimation of the contribution of aerosol swelling to the positive TCC-AOD relationship, which would not change our conclusions. Also, at the large scale at which we compute our correlations, it is likely that this effect is not extremely large. In contrast, the fact that aerosol swelling contributes significantly to the positive TCC-AOD relationship at the simulated large scales indicates the correlated influence of relative humidity on both aerosol optical depth and cloud fraction and demonstrates that this cannot be ignored in satellite based studies of the indirect aerosol effects (which are frequently performed using L3 data on similar scales). We added a paragraph explaining this to the revised manuscript.

Hypothesis 4: I'd find it very difficult to believe that model errors are better under-

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stood/ quantified than satellite retrieval errors at this point in time. If so, these error comparisons need to be presented here to make any statement about the satellite retrieval errors based solely on the difference in observed and simulated TCC-AOD relationships. Also, since the errors in estimating the other hypotheses using the model are very difficult (if not impossible) to present, it is not possible to make a statement such as that provided on line 1 of page 26021: that the difference between the simulated and observed relationships infers the amount of retrieval error. There is VERY LITTLE basis for that statement (even when it is qualified with a preliminary statement indicating that model processes are unlikely to be perfect!!).

We do not claim that the model errors are better understood than satellite retrieval errors, and we do not attempt to exactly quantify the amount to which satellite retrieval errors (cloud contamination and 3D effects) are responsible for the positive TCC-AOD relationship. We just document the finding that the model – which does not simulate 3D effects and cloud contamination – is not able to fully explain the positive relationship found in the retrievals. We think that there are two plausible explanations for this – 3D effects / cloud contamination (satellite retrieval errors) or model errors. We clarified this in the revised version, and would like to thank the reviewer for their suggestions which helped to improve the manuscript. However, we would like to point out that the analysis of satellite data alone does not allow insights into the causal relationship between TCC and AOD (even neglecting retrieval errors) and strongly believe that only the synergy between the two approaches, as presented here, can close this missing link.

Hypotheses 56: - Evaluation of these processes can not be justified without a thorough error analysis of the cloud microphysical processes in the model.

We agree, and make this more clear in the revised version. However our study finds that these effects are not dominant explanations for the positive TCC-AOD relationship. Given the uncertainties in the main contributors, an exact quantification using the GCM is impossible, and thus also a thorough error analysis of scavenging and aerosol cloud

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processing would not lead to new insights in the framework of the present analysis.

additional comments/questions:

We would like to thank the reviewer for highlighting these questions, and we revised the manuscript accordingly to include the necessary clarifications.

how/where is MODIS data used to calculate AOD (clear air vs. cloudy air)

MODIS only retrieves AOD in pixels analysed to be cloud-free.

To what extend does ice nucleation over polar and mid-latitude regions play into this comparison (i.e. presence of cirrus on satellite retrievals, and ice nucleation leading to glaciation of mixed-phase clouds)?

As can be seen in Supplementary Fig. 1, we do not find substantially different results for polar compared to tropical regions for the TCC-AOD relationships.

How does MODIS calculate TCC?

The cloud cover is determined as the number of pixels determined to be cloudy divided by the total number of pixels. The spatial scale of a pixel for the retrieval of cloud fraction is 1 km, and the cloud fraction then is used at the GCM grid scale.

How does the model calculate AOD?

For each of the seven log-normal modes the model calculates the complex volume weighted mean refractive index considering all aerosol components, including thermodynamically calculated aerosol water, which serve together with the ambient median radius as input to look-up tables from off-line Mie calculations. The calculations are performed on 24 wavelengths including the presented 550nm results.

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How does the model calculate aerosol swelling?

The water uptake calculation in HAM uses clear-sky relative humidity (computed from the grid-box mean and assuming saturation in the cloudy part of the grid-box). The water content for each mode is calculated from the internally mixed aerosol concentrations based on the ZSR- Relation (Zadanovskii, 1948; Stokes and Robinson, 1966) using binary molality coefficients from Jacobson et al. (1996). The derived equilibrium composition, including aerosol water, is used to calculate ambient median radii for each of the modes, which in turn serve as input to the aerosol radiation scheme described in the last paragraph (as well as to all other microphysical processes). It is worth pointing out that the consistency of this approach between water uptake and the other microphysical processes is still an exception in global aerosol modeling so that we understand the initial hesitation of the reviewers without further details.

Nucleation in the GCM? How is RH affected when droplets nucleate? How does this, in turn influence aerosol swelling?

The effect of nucleation on water vapour concentration is treated implicitly in the condensation scheme. The activation parameterization as described by Lohmann et al. (2007) influences the cloud droplet number concentration, but the generation of liquid water is done by the condensation scheme (Tompkins, 2002) using the subgrid-scale probability distribution (PDF) of total water within each grid-box. Where this PDF exceeds the saturation water vapour mixing ratio, determined from the grid-box temperature, the water in excess of saturation is assumed to condense, and the water vapour mixing ratio in the cloudy part of the grid-box is reduced by the amount of condensed water water to bring the cloudy-sky relative humidity down to saturation. Compared to the model time step, this is assumed to happen fast, allowing to use the above formula to compute clear-sky relative humidity.

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page 26019, line 19: this is pure speculation, and can not be supported without a thorough comparison of the differences between the two microphysical schemes!
While we tried already in the first manuscript version, we to clearly say that indeed here we only speculate, we revised the formulation in a way to be even more clearly in agreement with the reviewer on this.

Interactive comment on Atmos. Chem. Phys. Discuss., 9, 26013, 2009.