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Atmospheric Chemistry and Physics Discussions

Interactive comment on "Strong sensitivity of aerosol concentrations to convective wet scavenging parameterizations in a global model" *by* B. Croft et al.

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Author response to referee 2:

The authors thank referee 2 for this review, which has strongly contributed to the development of this manuscript.

RC: This manuscript presents an exercise in which a variety of wet removal schemes are applied to a GCM to investigate associated changes in aerosol optical depth. The new schemes show very clearly that "aerosol concentrations and wet deposition predicted in a global model are strongly sensitive to the assumptions made regarding the wet scavenging of aerosols in convective clouds". This fact is indisputable and after

reading and re-reading this manuscript numerous times I arrived at the conclusion that this message doesn't warrant a scientific publication. It is the kind of work that one expects to find in an Appendix: one or two simple plots justifying changes in a numerical scheme. I recognize that significant effort has gone into these simulations but that does not bring it closer to the threshold for what I would regard as publishable in a scientific journal.

AC: We wish to thank the referee 2 for giving our paper numerous readings and for this rigorous review. We agree that the presentation in the original version did not do our work justice. This study allows us to give consideration to much more than the conclusion that 'aerosol concentrations are strongly sensitive to the assumptions made regarding the wet scavenging of aerosols in convective clouds'. In this extensively revised version we focus more on the processes involved in convective wet scavenging (activation and impaction) and specifically we present an examination of the contribution of aerosols entrained above convective cloud bases to the wet removal attributed to activation and impaction scavenging in our global model simulations. We have further extended our analysis, and now consider how the simulated wet scavenging of accumulation and coarse mode aerosols entrained above cloud base has feedbacks on new particle formation, and in turn the number of Aitken mode aerosols in the framework of a GCM. We also examine the feedbacks on predicted cloud droplet number concentration (CDNC) and precipitation that occur in the GCM in the response to the scavenging-induced aerosol number changes. This revised version extends the analysis of our work much further than the original version, and this has prompted a title change to "Impact of entrained aerosols on convective wet scavenging in a global model". The abstract, discussion and conclusions section of this paper have been completely rewritten to present this more thorough analysis.

RC: Within the world of climate modeling I found the paper typical of GCM studies of clouds, aerosols and precipitation. It jumps between discussion of detailed effects of entrainment on supersaturation, suggesting an attempt to represent these processes (although they are unresolved by GCMs) and coarse treatment of drop nucleation, clouds, scavenging and precipitation. I suppose the excuse is that this is the best that climate models can do. But my numerous readings left me with a profound sense that if papers like this continue to be published we will simply be flooding the journals with excess technical material that does not further scientific understanding, and that raises a new generation of young scientists to believe that climate model clouds are real clouds.

AC: This revised version presents an analysis, which now goes beyond simply technical development of a model, as we state in the author comment above. We acknowledge that the treatment of many physical processes is, of necessity, rather coarse in a GCM. Indeed, we must ask the question 'are the current treatments of these processes adequate?'. Our work now contributes an evaluation of the representation of scavenging-induced aerosol-precipitation-aerosol feedbacks that occur in a GCM, and will hopefully motivate future work to improve not only our knowledge about activation and impaction processes in convective clouds, but also give insight on the importance of scavenging-induced changes on aerosol number predictions in a global model in terms of aerosol-precipitation-aerosol feedbacks.

We are able to use this work as an opportunity to consider these scavenging-induced aerosol-precipitation feedbacks that occur in a GCM. We find that the global and annual mean convective and stratiform precipitation change by about 15% between our model simulations. We examine the scavenging-induced changes to aerosol number burdens, which contribute to changes in simulated CDNC and in turn precipitation (both in a global, annual mean sense and in terms of the geographic distribution of these simulated fields). We find that simulated aerosol convective wet deposition is more strongly controlled by parameterizations for the wet scavenging of aerosols entrained above convective cloud bases than by precipitation changes, except for sea salt in the tropics. We point to the problems associated with prediction of moisture availability that limit our ability to have full confidence in aerosol-precipitation feedbacks in

a GCM. The work also now serves to further motivate the on-going need to improve the convective parameterizations beyond the bulk mass-flux approaches, and improve the representation of moisture fields in GCMs. Also, note that the latter paragraphs of the introduction have been revised (original paragraph 6 is removed) to eliminate the discussion of effects that are not under evaluation in this study.

We emphasize that we do not intend to send the message that climate model clouds are real clouds. On the contrary, our intention all along was to show that our predictions of aerosols are strongly limited by our lack of knowledge of cloud processes and our ability to represent these processes in GCMs. In addition, we have now added a paragraph to the introduction to emphasize that GCMs simulate ensembles of convective clouds as a single updraft plume, which has inherent limitations. Throughout the abstract and text we are now careful to note that these are simulated clouds. Particularly, in the new sections that discuss aerosol-precipitation feedbacks we are careful to acknowledge that these are simulated clouds and that there are issues related to prediction of moisture, which is available to the clouds in these simulations, which limit confidence in the aerosol-precipitation-aerosol feedbacks. We also now carefully acknowledge issues related to assumptions for the activation of aerosols in the model, which impact the CDNC prediction.

RC: In its current state, perhaps it has a place in ACP's technical notes. Following one potential avenue of enquiry below, it might potentially reach a level which would make it worthy of publication. That would require *major* changes and *major* effort.

AC: This revised version goes considerably beyond the original analysis, and we think that this revised version merits more than a technical note. The paper has undergone major revisions. The abstract, discussion and conclusion are now completely rewritten in order to present a more thorough analysis, and presentation of the findings of this study. We have also included new figures related to aerosol-precipitation-aerosol feedbacks (Figs. 7, 8, and 9). Further, we have introduced an additional simulation with a physically detailed parameterization of in-cloud impaction scavenging (simulation CF_imp), which allows us to better examine the role of activation versus impaction processes on wet scavenging in the context of a global model.

Major Points:

RC: 1) The connection between aerosol scavenging and precipitation may be a way to salvage this paper. These are two tightly coupled issues. Why not strengthen this connection *significantly*. If more aerosols are being removed how does this affect subsequent precipitation rates/amounts? This may require better treatment of coalescence scavenging and sub-cloud removal.(See points 2,4,5). A rigorous comparison with observed rainfall/aerosol distribution at shorter timescales than 5-year averages, and at selected regions might be useful. Extend yourselves! One more technical paper is clutter; one more good paper could be thought-provoking and useful.

AC: We have now specifically addressed the question 'if more aerosols are being removed how does this affect precipitation rates and amounts?'. Although our intention in the paper is to focus on the effects of clouds and precipitation on aerosol concentrations (rather than focusing primarily on the aerosol effects on clouds/precipitation), there are important feedbacks that occur because the aerosols in the model do affect precipitation rates that, in turn, affect the aerosol removal rates. Our additional discussion in the revised manuscript is included in Section 3.2. We examine the coupling between the modeled stratiform and convective cloud/precipitation response to scavenging-induced aerosol number changes in the ECHAM5-HAM global model. We have added figures that show geographic distributions of the aerosol number and precipitation response (Figs. 7 and 8) and made comparison with rainfall geographic distribution from the Global Precipitation Climatology Project (GPCP) (Fig. 9). We have also conducted comparisons with AERONET size distributions and with GPCP precipitation retrievals at shorter time-scales, considering the four seasons separately. We did not add these to the revised paper since the conclusions remain similar to those for the annual mean AOD and GPCP comparisons. We have also added Tables 4 and 6, which present the global, annual mean stratiform cloud properties and precipitation, and the global,

annual mean number burdens. In consideration of the reviewer's suggestion, we have included an additional simulation with a revised and more physically detailed treatment of impaction scavenging, which we think adds to the analysis of the results with respect to understanding the relative importance of activation and impaction for the simulated wet scavenging of aerosols in convective clouds. We have also added a more thorough description about the representation of autoconversion, aggregation and accretion in the model description section and emphasize that these effects are included in the aerosol wet scavenging parameterization.

RC: 2) How is autoconversion affected by changes in scavenging schemes. Is CDNC influenced by autoconversion and accretion? (It should be, although the paper makes no mention of this.)

AC: Yes, the CDNC is influenced by autoconversion and accretion. We now make this clear in the model description (second paragraph of Section 2). Also, the new section 3.2 specifically discusses how the scavenging schemes influence the aerosol number and hence the CDNC, which in turn affects the autoconversion. In this new section we review the influence of changes in CDNC on precipitation formation in the model based on the parameterization for these processes in the GCM. In the GCM, autoconversion rates depend inversely on CDNC and increase with increases in liquid water content. Among our five simulations, the reduction in CDNC (associated with a scavenging-induced reduction in number of soluble Aitken mode aerosols available to the activation scheme) was found to increase the frequency of convective precipitation formation at lower altitudes, which led to a 15% increase in global, annual mean convective precipitation. As a result, there was less moisture available to the stratiform clouds since global and annual mean evaporation from the surface did not change. As a result the stratiform liquid water path was reduced by 20% and stratiform cloud cover was reduced by 5% and stratiform precipitation reduced by 15%. While this is thought-provoking to consider these feedbacks, we emphasize in our discussion that there is uncertainty about these responses due to issues related to the parameterization of moisture availability in convective clouds. However, these scavenging-induced aerosol-precipitation feedbacks, and this coupling between the stratiform and convective cloud responses in a closed system with a fixed annual mean evaporation rate are an important considerations for users of global models.

RC: 3) The section comparing to profiles from Koch is so superficial that it has no place in the paper. This kind of work does our field a disservice. If the authors want to compare to observations, please do this with rigorous scientific method, backed by statistical analysis. The fact that one of the schemes compares better with MODIS than others is not particularly useful since so many other processes could be tuned to achieve better results. (See points 2,4,5.)

AC: We have now included in the discussion that these comparisons should not be over-interpreted for reasons related to the different spatial and temporal averaging between the model and the retrievals (last paragraph of Section 3.1.1). We have kept the figure in the paper since convective scavenging has important implications for the vertical profiles of aerosols, although we acknowledge that global datasets to validate global aerosols profiles are lacking. We have added a statistical analysis to this figure, and also to the figure that makes the comparison with MODIS/MISR/AERONET aerosol optical depth. The text now also includes a note that the model has not been re-tuned between the simulations so that any changes in the simulated concentrations and AOD can be attributed to the changes in model process representations, and not attributed to model re-tuning.

RC: 4) Aerosols seem to be released as a result of B-F. How about through drop evaporation or ice sublimation?

AC: Yes, aerosols are released because of the Bergeron-Findeisen process. Also, evaporation of precipitation is included and this process releases aerosols in our model. For the convective clouds in our model, the CDNC is transported upwards within the context of the mass flux scheme - as the mass flux decays, less CDNC is transported

upwards, which implicitly allows for drop evaporation and ice sublimation (and aerosol release), much like CDNC evaporation in the statiform scheme occurs implicitly due to changes in cloud cover. Also for the simulation CF_ed, droplet evaporation/aerosol release from droplets is parameterized to occur due to detrainment of cloud droplets from the updraft shaft. The detailed description of the included convective microphysics is found in Lohmann (2008).

RC: 5) We know that sub-cloud impaction scavenging can be responsible for 15% of mass removal. This is brushed off as something to look at in the future (!)

AC: We agree that sub-cloud impaction is a process that needs to be carefully addressed in global models. Treatment of sub-cloud impaction is included in our model. However, we did not re-parameterize this process within this study since we wanted to focus on the in-cloud processes, activation, impaction, and entrainment above cloud base. Particularly for convective clouds, representation of sub-cloud impaction is not straightforward (due to precipitation potentially falling out of the cloud at many levels) and we did not want to introduce a revised parameterization that was not carefully developed. For sub-cloud impaction, the issue of the parameterization of the convective precipitating fraction of the GCM grid-box has a key role to play, and most GCMs parameterize this with assumed fixed updraft velocities, which introduce a certain bias into the models. Also there may be below-cloud impaction scavenging that occurs in partly cloudy grid boxes when rain falls out of the side of a slanted rain shaft, whereas our parameterization requires a completely cloud-free grid box. Improvements require an examination of the parameterization of convective cloud-fraction, which again is not particularly well treated in GCMs at the moment. We acknowledge that this sub-cloud impaction process does need to be improved in GCMs, but we did not wish to introduce a haphazard correction, so for the purposes of this study we choose to keep this parameterization fixed. We have added a discussion of these issues to fourth paragraph of Section 2.

RC: 6) Huge changes in CDNC (doubled in the mid troposphere) should provide hints that something is wrong. These are not real clouds!

AC: This revised version presents a discussion of how the scavenging-induced changes to aerosol number influence the CDNC, which in turn feedback on precipitation in the ECHAM5-HAM model. Specifically, we acknowledge that the activation parameterization used for this study does allow Aitken mode aerosols larger than 25nm in radius to participate in the convective activation scheme. Thus, Aitken mode number concentrations strongly control CDNC in our model. Certainly we are not at the point in GCMs where we can claim high confidence in our convective cloud simulations! However, we agree that this study provides a thought-provoking opportunity to consider the feedbacks between aerosols and precipitation that do occur in a GCM in response to a change in the aerosol number burden induced by the assumption that aerosols entrained above cloud base are either negligibly or vigorously scavenged. Our results highlight the importance of the moisture fields in the model and motivate the importance of ongoing work to improve the representation of these fields within the context of convective parameterizations. Throughout the revised discussion we emphasize that these are simulated clouds, not real clouds and the modeled response is dependent on the parameterizations for that processes implemented in the global model.

Interactive comment on Atmos. Chem. Phys. Discuss., 12, 1687, 2012.