Constraining cloud droplet number concentration in GCMs suppresses the aerosol indirect effect

C. Hoose,1 J. E. Kristjánsson,1 T. Iversen,2 A. Kirkeväg,2 Ø. Seland,2 and A. Gettelman3

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Global aerosol-climate models with prognostic treatment of cloud droplet number concentration (CDNC) often prescribe lower bounds for CDNC or aerosol concentrations. Here we demonstrate that this possibly unphysical constraint reduces the simulated aerosol indirect effect by up to 80%, caused by extensively uniform CDNCs. In present-day conditions, the impact of the prescribed lower bound for CDNC is mainly visible over oceans, while with preindustrial emissions, large parts of both land and ocean areas are influenced. We furthermore show that imposing the same constraints on aerosol instead of on CDNC reduces the aerosol indirect effect to a lesser extent. Citation: Hoose, C., J. E. Kristjánsson, T. Iversen, A. Kirkevåg, Ø. Seland, and A. Gettelman (2009), Constraining cloud droplet number concentration in GCMs suppresses the aerosol indirect effect, Geophys. Res. Lett., 36, L12807, doi:10.1029/2009GL038568.

1. Introduction

Aerosol particles influence clouds and the hydrological cycle by their ability to act as cloud condensation nuclei. Depending on composition and size, they form cloud droplets at a certain supersaturation. Anthropogenic activity has led to higher aerosol concentrations, which results in more activated droplets, smaller droplet sizes (at a given cloud liquid water content) and a higher cloud albedo (indirect cloud albedo effect). Possibly, the precipitation efficiency is simultaneously decreased (indirect cloud lifetime effect) [Lohmann and Feichter, 2005].

Global climate models with double-moment aerosol and cloud microphysics schemes are particularly well suited for the calculation of aerosol indirect effects, but face specific challenges. Numerous free parameters contribute to the simulated cloud droplet number concentration (CDNC), even if a model includes a fully coupled aerosol-cloud scheme. These parameters and associated processes are: prognostic aerosol number concentrations and composition, a parameterization of cloud droplet activation (which in turn depends on the aerosol concentration, composition, and on meteorological conditions), and sink terms for cloud droplets (evaporation, collision-collection processes). To avoid CDNC values which are considered too low, some models impose a lower bound, irrespective of the simulated concentration of activated aerosol particles. Typical values of this lower bound range between 5 and 40 cm⁻³. In the Hadley Center climate model [Jones et al., 2001], the lower bound is 35 cm⁻³ over ice-free land and 5 cm⁻³ elsewhere. ECHAM4 and ECHAM5 apply a minimum value of 40 cm⁻³ [Lohmann et al., 1999, 2007]. In SPRINTARS [Takemura et al., 2005], a lower bound for the aerosol number concentration instead of for the CDNC is applied, and it is set to 300 cm⁻³, whereas CDNC is applied, and it is set to 300 cm⁻³ over land and to 30 cm⁻³ over ocean. Wang and Penner [2009], in IMPACT-CAM, use a lower bound for CDNC of 20 cm⁻³ and motivate this by a possible underprediction of fine mode sea salt aerosol. In addition, they show that the simulated cloud albedo effect is sensitive to this value, as also demonstrated by Lohmann et al. [2000] and Ghan et al. [2001]. On a similar note, Kirkeväg et al. [2008] show that adding 15 cm⁻³ to the CDNC everywhere, as a proxy for natural background aerosols which are not included in the model (nitrate, biological particles), reduces the simulated aerosol indirect effect (the change in shortwave cloud forcing) by 42%.

Observed CDNCs can reach very low values in clean conditions. For example, McFarquhar et al. [2007] report aircraft CDNC measurements in Arctic mixed-phase clouds with spiral-averaged values down to 23 ± 10 cm⁻³. Gupte and Isaac [2004] examine the temperature dependence of CDNC in liquid-only conditions from measurements in Arctic clouds, maritime boundary-layer clouds, and winter storms, and report concentrations of ~1–3 cm⁻³ at about −35°C. Yum et al. [1998] find CDNCs down to 17 ± 27 cm⁻³ in summertime stratuscumulus clouds in the Southern Oceans. In the Tropical Atlantic, at 8°S, CDNC of 7–10 cm⁻³ have been observed in airmasses which presumably originated from the Southern Oceans and had not been in contact with polluted air for many days [Bower et al., 2006]. The satellite retrieval by Bennartz [2007] shows large areas over remote oceans with annual mean CDNCs in the marine boundary layer below 40 cm⁻³, with minima around 20 cm⁻³. For example, the mean CDNC in the South Pacific, more than 1500 km from the next land mass, is found to be 40 ± 16 cm⁻³, and 32 ± 7 cm⁻³ when only clouds with a high likelihood of drizzle are considered.

As the aerosol indirect effect is calculated as the difference between model simulations with present-day and with preindustrial aerosol and precursor emissions, special attention has to be paid to the effect of CDNC constraints in the preindustrial setup. Without anthropogenic emissions, aerosol concentrations and CDNCs are significantly lower than in present-day conditions, also over land. Andreae [2007] states that prehuman cloud condensation nuclei concentrations “may have been very similar over continents and oceans, ranging from a few tens per cm² in biogenically inactive regions or seasons to a few hundreds per cm³ under biologically active conditions”. Therefore a
too high minimum value can introduce errors in the simulated aerosol indirect effect over wide areas of the globe.

[6] In this article, we systematically investigate the effect of different lower bounds on either CDNC or aerosol concentrations for present-day and preindustrial CDNC fields and for the aerosol indirect effect. Our tool is the global climate model CAM-Oslo, which is described in the next section.

2. Model Description

2.1. CAM-Oslo

[7] The aerosol-climate model CAM-Oslo is based on the Community Atmosphere Model CAM3 [Collins et al., 2006]. It has been extended to include a detailed aerosol module [Seland et al., 2008] and a prognostic double-moment cloud microphysics scheme [Storelvmo et al., 2006, 2008], which allows the calculation of aerosol indirect effects. In this study, only effects via liquid water clouds are considered. We describe here a few recent updates to the model. The activation of aerosol particles into cloud droplets is calculated at all cloudy gridpoints as a function of aerosol composition and the subgrid-scale updraft velocity [Abdul-Razzak and Ghan, 2000]. For the simulations presented here, the subgrid-scale updraft velocity \( w_{turb} \) is calculated following Morrison and Gettelman [2008]:

\[
w_{turb} = \max \left( 10 \text{ cm s}^{-1}, \frac{K}{l_c} \right)
\]

where \( K \) is the turbulent exchange coefficient, and \( l_c \) the mixing length, set to a constant value of 30m. The simulated droplet concentrations are sensitive to the lower bound on \( w_{turb} \). The activation calculation now uses look-up tables for aerosol modal radii and standard deviations which are allowed to vary as the aerosol grows, instead of assuming constant modal radii as was done by Storelvmo et al. [2006, 2008]. Particles in the internally mixed modes containing sulfate, organic carbon and black carbon or dust are assumed as coated black carbon/dust cores whenever the coating thickness is larger than 2nm (corresponding to about 1–4 monolayers). The particle hygroscopicity is then determined by the hygroscopicity of the coating, calculated as a volume mixture of sulfate and organic carbon.

[8] As common in global climate models, the double-moment microphysics scheme is applied only to long-lived stratiform clouds. Liquid condensate which is detrained from convective clouds is added to the stratiform condensate with a prescribed droplet radius. Instead of using a fixed radius, we use a simple aerosol-dependent function based on a fit through simulated effective radii for idealized convective clouds by Choularton and Bower [1993]. Choularton and Bower [1993] found that due to dry-air entrainment, the effective radius is only a weak function of height, but most strongly influenced by the cloud condensation nuclei spectrum at cloud base. Therefore we parameterize the effective droplet radius of the detrained droplets, \( r_{eff} \) (in \( \mu m \)), as a function of the concentration of cloud condensation nuclei activated at 1% supersaturation, CCN, in \( \text{cm}^{-3} \).

\[
r_{eff} = 2.1 + 66.25 \times \max(10, \text{CCN})^{-1/3}
\]

The CCN concentration at 1% supersaturation is not explicitly calculated, but as a simple guess it is assumed to be twice the amount of activated aerosol from the stratiform cloud scheme \( N_{act} \). The factor 2 is applied because supersaturations reached in stratiform clouds are usually lower than 1%. With these assumptions, \( r_{eff} \) varies between about 7 \( \mu m \) in polluted conditions and 32 \( \mu m \) in very clean conditions. The in-cloud scavenging coefficient for mineral dust is reduced from 1 in Seland et al. [2008] to 0.1, resulting in less wash-out, and consequently increased cloud condensation nuclei concentrations in dust-influenced regions. All other parameterizations are the same as described in Storelvmo et al. [2006] and Seland et al. [2008].

2.2. Set-Up of the Experiments

[9] In several sensitivity experiments, constraints on the CDNC are imposed. In a first series, the in-cloud droplet concentration \( N_i \) is not allowed to be lower than a prescribed value, CDNCmin.

\[
N_i = \max(\text{CDNCmin, } N_i)
\]

The lower bound CDNCmin is set to \( 10^{-10} \) (labelled 0 in the following), 10, 20, 30 and 40 \( \text{cm}^{-3} \), respectively. While CDNCmin = \( 10^{-10} \text{ cm}^{-3} \) is applied in the control experiment to avoid numerical problems and has no physical meaning, the higher lower bounds constitute a way of tuning the simulated indirect effect to less negative values, as applied in other models.

[10] In a second series of experiments, a lower bound is imposed on the number concentration of aerosols available for activation as follows: First, the concentration of activated particles \( N_{act} \) is calculated starting from the simulated aerosol composition, concentration and size distribution. If \( N_{act} \) is smaller than the lower bound AEROmin, then the difference between AEROmin and \( N_{act} \) is added in form of pure sulfate aerosols with a radius of 75nm (SO4_{75nm}), and the activation is recalculated (\( \tilde{N}_{act} \)). In symbolic notation:

\[
N_{act} = f(\text{aerosol})
\]

\[
\tilde{N}_{act} = f(\text{aerosol}) + \max((\text{AEROmin} - N_{act}), 0) \times \text{SO4}_{75nm}
\]

\( f(\text{aerosol}) \) denotes a functional dependence on aerosol composition, number concentrations and size distributions. AEROmin is set to 10, 20, 30 and 40 \( \text{cm}^{-3} \), respectively. The aerosol is added only for the calculation of activated droplets and does not influence the aerosol life cycle scheme. In these simulations, CDNCmin is kept at \( 10^{-10} \text{ cm}^{-3} \).

Constraining the aerosol number can be considered a more physical way of achieving higher CDNC in global models, which do not include all natural aerosol species.

[11] All simulations are run in T42 resolution (2.8125 \( \times \) 2.8125\( \times \)), with 26 vertical levels. The simulations are integrated for 5 years after 4 months of spin-up, for present-day and preindustrial aerosol emissions. In the following, the 5-year mean values are given with standard error (given by the standard deviation divided by the square root of the number of simulated years). Both the cloud
albedo effect and the cloud lifetime effect are included in the model and are influenced by CDNCmin and AEROmin.

3. Results and Discussion

[12] The simulated CDNC fields at model level $\eta = 0.87$ (about 870 hPa) are shown in Figure 1. In the control run, without any prescribed lower bounds (CDNCmin = 0 cm$^{-3}$), the annual mean concentrations at this level are below 10 cm$^{-3}$ over the Southern Oceans (probably somewhat too low, compared to Bennartz [2007]) and reach values around 200 cm$^{-3}$ in present-day polluted regions. Closer to the surface (not shown), the highest simulated annual mean present-day values are around 750 cm$^{-3}$. By comparison, the preindustrial simulation exhibits lower values, primarily over land, which results in a lower land-sea contrast. In the present-day simulations, the prescribed CDNCmin has mainly an effect over ocean, where cloud condensation nuclei concentrations are low. The continental clouds are frequently influenced by pollution and have CDNC concentrations above the lower bound. In the preindustrial simulations, the concentrations over land are also significantly altered by the lower bound, due to much cleaner background aerosol concentrations than with present-day emissions. With CDNCmin = 20 and 40 cm$^{-3}$, the CDNCs over ocean are very uniform and similar in present-day and preindustrial conditions.

[13] In contrast, prescribing AEROmin (Figure 1b) has less drastic effects than prescribing the same values of CDNCmin. With AEROmin = 10 cm$^{-3}$, the mean CDNC at 870 hPa remains nearly unaffected, and with AEROmin = 20 cm$^{-3}$, the effect is about as pronounced as with CDNCmin = 10 cm$^{-3}$. With AEROmin = 40 cm$^{-3}$, present-day and preindustrial CDNC fields over ocean have converged.

[14] The difference in short-wave cloud forcing between present-day and preindustrial simulations, $\Delta$SWCF, is visualized as a function of CDNCmin and AEROmin in Figure 2a. $\Delta$SWCF can be taken as a measure of the aerosol indirect effect. The global mean $\Delta$SWCF is reduced by 67% from $-1.88 \pm 0.14$ to $-0.62 \pm 0.17$ W m$^{-2}$ when CDNCmin is increased from 0 to 40 cm$^{-3}$. It is remarkable that the reduction is already nearly equally severe with CDNCmin = 20 or 30 cm$^{-3}$ to what it is for CDNCmin = 40 cm$^{-3}$. By splitting up $\Delta$SWCF into the contributions from land and ocean areas, we find that the lower bound on CDNC mainly reduces the aerosol indirect effect over ocean, which is reduced by over 80% from $-1.79 \pm 0.19$ to $-0.33 \pm 0.18$ W m$^{-2}$ when CDNCmin is increased from 0 to 40 cm$^{-3}$. Although the mean CDNC fields over ocean show little difference between present-day and preindustrial when the strongest constraints are imposed (Figure 1), $\Delta$SWCF is not reduced to 0 over ocean because of vertical and temporal variations, which are not visible in the annual mean fields at one level. Over land, $\Delta$SWCF is
Figure 2. Difference in short-wave cloud forcing (SWCF) (a) between present-day and preindustrial simulations as a function of CDNCmin and AEROmin, as global mean, over ocean and over land and (b) compared to model versions with different aerosol-cloud microphysics treatments and to previously published results for the cloud albedo effect. The error bars represent the standard error.

4. Conclusions

[16] In this study, we have demonstrated that the common practice of prescribing a lower bound for CDNC in global climate models significantly reduces the simulated aerosol indirect effect. Our systematic investigations show a similar reduction to the results by Lohmann et al. [2000] with ECHAM4 and by Wang and Penner [2009] with IMPACT-CAM for the cloud albedo effect only (Figure 2b). Simulations are also shown for NCAR CAM3 with a different two-moment microphysics scheme by Gettelman et al. [2008], and a different aerosol model (the MOZART Bulk Aerosol Model (BAM) [Tie et al., 2005]), but a similar formulation of droplet activation [Abdul-Razzak and Ghan, 2000], and for CAM-Oslo with a diagnostic CDNC scheme, using prescribed supersaturations [Kirkevåg et al., 2008]. All these models, with different degrees of complexity regarding the aerosol and cloud microphysics formulation, react similarly to the prescribed CDNCmin, which indicates that the model used in this study has a representative sensitivity to this assumption. [17] As marine CDNCs are generally lower than continental CDNC, the prescribed lower bound has the strongest impact over the oceans. Already by prescribing a minimum CDNC of 20 cm\(^{-3}\), the difference between present-day and preindustrial conditions in SWCF over oceans is reduced by over 70%. The CDNCmin constraint implies the elimination of aerosol indirect effects in the cleanest, and therefore most susceptible, regions. [18] Furthermore, experiments with a constraint on aerosol number concentration instead of a constraint on CDNC have shown that possibly underpredicted aerosol concentrations are not an adequate justification for a lower bound on CDNC. As the CDNC is not only determined by the cloud condensation nuclei concentration, but also by the activation efficiency (in-cloud supersaturation) and by the sink terms (collection processes), adding more aerosols (although good cloud condensation nuclei) does not increase CDNC by the same amount. For the values of 10, 20 and 30 cm\(^{-3}\), the reduction in ΔSWCF is therefore also weaker in the AEROmin simulations than in the CDNCmin simulations. Only with a lower bound on the aerosol number concentration of 40 cm\(^{-3}\) is the global aerosol indirect effect reduced to a similar extent as with CDNCmin = 40 cm\(^{-3}\), because it is eliminated over wide ocean areas.

[19] These results leave the modeling community with the dilemma that large magnitude negative aerosol indirect effects (lower than about \(-1.2 \text{ W m}^{-2}\)) are not in agreement with inverse calculations [Hegerl et al., 2007] and satellite estimates [e.g., Quaas et al., 2008]. It might be argued that it is not clear how common droplet concentrations below 10 cm\(^{-3}\) or 20 cm\(^{-3}\) are in nature, as observations in remote regions are scarce, and that the lower bound can be justified for present-day climate, dismissing observations below those values as rare exceptions. However, in preindustrial climate, CDNCs were certainly lower than in today’s conditions. It is likely that occurrences of CDNC below 10 cm\(^{-3}\) or 20 cm\(^{-3}\) were more frequent, and that a constraint on the CDNC influences simulated clouds stron-
ly and unphysically. Therefore it is important to seek more physical explanations for the assumed overestimation of the aerosol indirect effect, e. g. aerosol species which are missing in the models, or aerosol indirect effects associated with mixed-phase and ice clouds.

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