Global impacts of anthropogenic aerosols on convective clouds and precipitation

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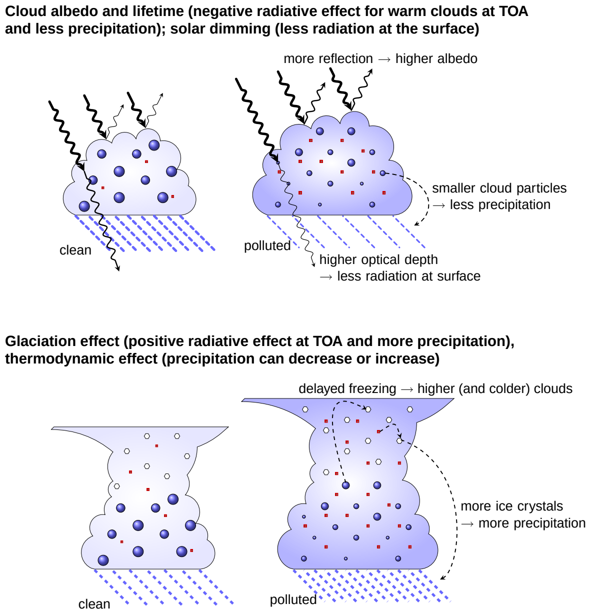
1. Introduction

Aerosols are an integral part of the atmospheric hydrological cycle and the atmospheres radiation budget, with many possible feedback mechanisms that are not fully understood yet. Human activities modify through direct emission and secondary formation processes aerosol parameters and cloud properties in warm, mixed-phase and ice clouds. The easiest understood interaction between aerosols and climate is the direct effect (scattering and absorption of shortwave and thermal radiation). In addition, interactions of aerosols with the hydrological cycle, and additional impacts on the radiation budget, occur through the role of aerosols in cloud microphysical processes, as aerosol particles act as cloud condensation nuclei and ice nuclei as summarized in Figure 1. Because clouds in mid-latitudes originate predominately via the ice phase, changes of the properties of ice nuclei are of crucial importance for the hydrological cycle. An increase in ice nuclei can result in a rapid glaciation of a supercooled liquid water cloud due to the difference in vapour pressure over ice and water. Unlike cloud droplets, these ice crystals grow in an environment of high supersaturation with respect to ice, quickly reaching precipitation size, and with that can turn a non-precipitating into a precipitating cloud (glaciation effect).

The impact of aerosols on convective clouds is not known yet. Previous estimates of changes in convective precipitation from individual cloud systems due to anthropogenic aerosols are inconclusive, with suggestions for precipitation enhancement or suppression (Lohmann and Feichter 2005). A few of these studies are described below.

Rosenfeld (1999) and Rosenfeld and Woodley (2000) analyzed aircraft data together with satellite data suggesting that pollution aerosols suppress deep convective precipitation by decreasing cloud droplet size and delaying the onset of freezing. This hypothesis was supported with a cloud resolving model (Khain et al. 2001) such that supercooled cloud droplets down to -37.5°C could only be simulated if the cloud droplets were small and numerous. On a global scale, Nober et al. (2003) find large instantaneous local aerosol forcings that reduce the warm phase precipitation in convective clouds by this mechanism. The precipitation change at the surface is, however, guided by feedbacks within the system.


Cloud albedo and lifetime (negative radiative effect for warm clouds at TOA and less precipitation); solar dimming (less radiation at the surface)

Glaciation effect (positive radiative effect at TOA and more precipitation), thermodynamic effect (precipitation can decrease or increase)

Figure 1: Schematic of the different aerosol effects on clouds and precipitation.

Khain et al. (2005) postulated that smaller cloud droplets, such as those originating from human activity, would reduce the production of drizzle drops. When these droplets freeze, the associated latent heat release results in more vigorous convection. In a clean cloud, on the other hand, drizzle would have depleted the cloud so that less latent heat is released when the cloud glaciates resulting in less vigorous convection. Therefore, a squall line is only simulated under the influence of higher continental

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aerosol concentrations and results in more precipitation after two hours of simulations. More precipitation from polluted clouds is also simulated for different periods in Oklahoma (Zhang et al. 2005) as well as for multicell cloud systems (Seifert and Beheng 2006). On the other hand, precipitation from single mixed-phase clouds is reduced under continental and maritime conditions when aerosol concentrations are increased (Khain et al. 2004; Seifert and Beheng 2006). Modelling results of a thunderstorm in Florida suggest that the whole dynamic structure of the storms is influenced by varying dust concentrations (Van den Heever et al. 2006). In particular, the simulated updrafts are consistently stronger and more numerous when Saharan dust is present compared with a clean air mass. This suggests that dust enhanced glaciation of convective clouds leading to dynamical invigoration of the clouds, and thereby enhanced rainfall at the ground (as discussed above). However, the simulated precipitation enhancement only lasted two hours after which it decreased as compared with clean conditions.

2. Model description

Here we use the ECHAM5 general circulation model (GCM) (Roeckner et al. 2003) to estimate the importance of aerosol effects on convective clouds. The version of ECHAM5 used in this study includes the double-moment aerosol scheme ECHAM5-HAM that predicts the evolution of an ensemble of microphysically interacting internally- and externally-mixed aerosol populations as well as their size distribution and and composition (Stier et al. 2005). The size-distribution is represented by a superposition of log-normal modes including the major global aerosol compounds sulfate, black carbon, organic carbon, sea salt and mineral dust. It also includes prognostic equations of the mass mixing ratios of cloud liquid water and ice and number concentrations of cloud droplets and ice crystals (Lohmann et al. 1999; Lohmann 2002; Lohmann and Diehl 2006).

The cloud microphysics scheme has been extended from stratiform clouds to convective clouds (Zhang et al. 2005). So far the convective microphysics scheme had not been coupled to an aerosol scheme. Here we couple it to ECHAM5-HAM by adopting the aerosol activation scheme according to Lin and Leaitch (1997) also for convective clouds:

$$Q_{nucl} = \max\left[\frac{1}{\Delta t}\left(0.1(N_l^{max})^{1.27} - N_{old}\right), 0\right] \quad (1)$$

where

$$N_l^{max} = \frac{N_a w}{w + \alpha N_a} \quad (2)$$

and α = 0.023 cm^4 s^{-1}. N_a is the number concentration of the internally mixed aerosols larger than 0.035 μm in radius. The updraft velocity w is obtained as the sum of the grid mean vertical velocity $\overline{w}$ and a turbulent contribution expressed in terms of the turbulent kinetic energy (TKE) for stratiform clouds (Lohmann et al. 1999). In terms of convective clouds also a contribution of the convectively available potential energy (CAPE) (Lohmann 2002) has been added:

$$w = \begin{cases} \overline{w} + 1.33\sqrt{TKE} & \text{strat. clouds} \\ \overline{w} + 0.5\sqrt{CAPE} + 1.33\sqrt{TKE} & \text{conv. clouds} \end{cases} \quad (3)$$

The other microphysical processes include autoconversion of cloud droplets to form rain, accretion of cloud droplets with rain drops, self collection of cloud droplets, heterogeneous freezing of cloud droplets by contact and immersion freezing between 0 and -35°C, homogeneous freezing of cloud droplets below -35°C, aggregation of ice crystals to form snow, accretion of snow flakes with cloud droplets and ice crystals, sedimentation of ice crystals and snow flakes and evaporation of rain drops and sublimation of snow flakes.

For calculations of the cloud albedo effect, the influence of anthropogenic aerosols on the shape of the cloud droplet size spectra (dispersion effect) has been taken into account. It is included in relating the cloud droplet effective radius r_e to the mean volume radius r_v:

$$r_e = \beta\, r_v = \beta\, \sqrt[3]{\frac{3\, LWC}{4\, \pi\, \rho_w\, N_l}} \quad (4)$$

where ρ_w is the water density, LWC is the cloud liquid water mass mixing ratio and the scaling factor β is related to the cloud droplet number concentration (Peng and Lohmann 2003):

$$\beta = 1.18 + 0.00045 N_l \quad (5)$$

3. Preliminary results

All simulations have each been carried out in T42 horizontal resolution (2.8125° × 2.8125°) with climatological sea surface temperature and sea-ice extend. ECHAM5conv does include microphysics in convective clouds whereas ECHAM5ctl does not. Both simulations have been repeated using emissions representative for 1750 (Stier et al. 2006). The results for ECHAM5ctl and ECHAM5conv described below have been carried out for 3 years after an initial spin-up of 3 months. However, these first results are still very preliminary.

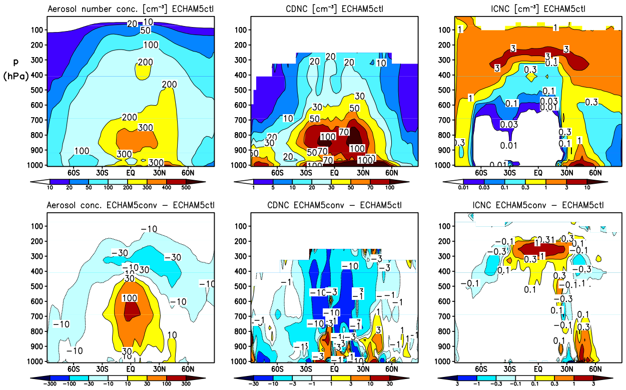

Figure 2: Annual zonal mean pressure versus latitude distribution of the aerosol number concentration $>$ 0.035 μm in radius that participate in the activation process, cloud droplet number concentration (CDNC) and ice crystal number concentration (ICNC) sampled over the cloudy part of the grid whenever clouds are present in ECHAM5ctl and the difference between ECHAM5conv-ECHAM5ctl.

These preliminary results indicate that more aerosols are retained in the lower and middle tropical troposphere in ECHAM5conv. This results from reduced drizzle formation in convective clouds because of the higher cloud droplet number concentration below 800 hPa (Figure 2). Instead more cloud droplets freeze increasing the ice crystal number concentration. Because the precipitation formation via the ice phase is more efficient than in warm clouds, these glaciated clouds have a shorter lifetime than supercooled water clouds (Rogers and Yau 1989; Lohmann and Diehl 2006). Thus, the global mean precipitation increases from 2.82 mm/d in ECHAM5ctl to 2.85 mm/d in ECHAM5conv and total cloud cover decreases from 61.6% to 60.3%.

The faster aerosol removal in ECHAM5conv also results in a smaller increase in liquid water path when going from pre-industrial times to present day (5.4 g m^{-2} as compared to 9.9 g m^{-2} in ECHAM5ctl). The smaller increase in liquid water path in ECHAM5conv is in better agreement with AVHRR satellite data which show no systematic trend of liquid water path on column aerosol number over the full range of column aerosol number concentration (Nakajima et al. 2001).

The glaciation effect in convective clouds is very noticeable in ECHAM5conv because it turns the small increase in ice water path in ECHAM5ctl into a decrease (Table 1). This causes the total anthropogenic aerosol effect to be reduced from -2.7 W m^{-2} in ECHAM5ctl to -1.8 W m^{-2} in ECHAM5conv. The smaller indirect effect in ECHAM5conv is more in-line with inverse estimates of the indirect effect that start from the observed land and ocean warming (Anderson et al. 2003).

Simulation	ECHAM5ctl	ECHAM5conv
ΔLWP, g m^{-2}	9.9	5.4
ΔIWP, g m^{-2}	0.3	-3.7
ΔTCC,%	1.4	0.2
ΔPR, mm d^{-1}	-0.015	-0.026
ΔF$_{net}$, W m^{-2}	-2.7	-1.8

Table 1: Global annual mean changes present-day - 1750 in liquid water path (LWP), ice water path (IWP), total cloud cover (TCC), precipitation (PR) and net radiation at the top-of-the-atmosphere (F$_{net}$) for the two pairs of simulations.

4. Summary and conclusions

Preliminary results suggest that including cloud microphysics in convective clouds moderates the indirect aerosol effect because it enhances the precipitation via the ice phase and thus removes more aerosols from the atmosphere.

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