Representing cloud-aerosol interactions in GCMs

Ulrike Lohmann

ETH Zurich, Institute for Atmospheric and Climate Science
8092 Zurich, Switzerland
ulrike.lohmann@env.ethz.ch

ABSTRACT

Aerosol-cloud interactions still constitute the largest uncertainty in terms of radiative forcing or adjusted forcing since pre-industrial times. Here, I present some of the progress that has occurred since the fourth assessment report (AR4) of the Intergovernmental Panel on Climate Change (IPCC) and discuss some of the reasons for it.

1 Introduction

The radiative forcing (RF) due to the influence of aerosols on the microstructure of clouds (formerly called the first indirect aerosol effect, cloud albedo effect or Twomey effect) is still rather uncertain. In the fourth assessment report (AR4) of the Intergovernmental Panel on Climate Change (IPCC) it was estimated with -0.7 W m^{-2} with a range between -1.8 to -0.3 W m^{-2} (Forster et al., 2007). In addition to the RF, where the anthropogenic aerosol perturbation to the cloud albedo is defined for a constant liquid water content, fast adjustments occur. These include changes to the cloud lifetime, extent and phase. Taking them into account results in the so-called adjust forcing due to aerosol-cloud-interactions (AFaci). Together with the adjusted forcing due to aerosol-radiation interaction (AFari), the total adjusted forcing (AFari+aci) was estimated to be -1.2 W m^{-2} with a range between -2.3 to -0.2 W m^{-2} in AR4 (Denman et al., 2007).

Since AR4, more than 35 papers appeared in which either RFaci, AFaci or AFaci+ari have been estimated from global climate models (GCMs). In addition several papers used satellite data either in combination with GCMs or by themselves to estimate RFaci or AFaci. A few of these studies will be discussed in more detail below.

2 Progress since AR4

Storelvmo et al. (2009) studied the sensitivity of RFaci due to the different empirical relationships that were used to calculate the cloud droplet number concentration (CDNC) in those GCMs that were used in AR4 for future projections. Of the 23 models or model versions that were used in AR4 for future projections (Meehl et al., 2007), only 9 included aerosol-cloud interactions. Of those, most of them only considered RFaci but neglected the fast adjustments. Of the models that calculated RFaci, only 3 of the models included an online sulfur cycle and all except one used empirical relationships to calculate the CDNC. Storelvmo et al. (2009) noticed that the models had a spread of 2.2 W m^{-2} in the shortwave forcing for the year 2000 and asked how much of this spread can be explained by the different empirical relationships that were used to obtain CDNC. Because the empirical relationships differ vastly, also the anthropogenic change in CDNC at 950 hPa ranges between 10 and 120 cm^{-3}, 1.3 W m^{-2} of the 2.2 W m^{-2} spread in present-day shortwave forcing can be explained by these different methods to predict CDNC from sulfate aerosols (Figure 1).

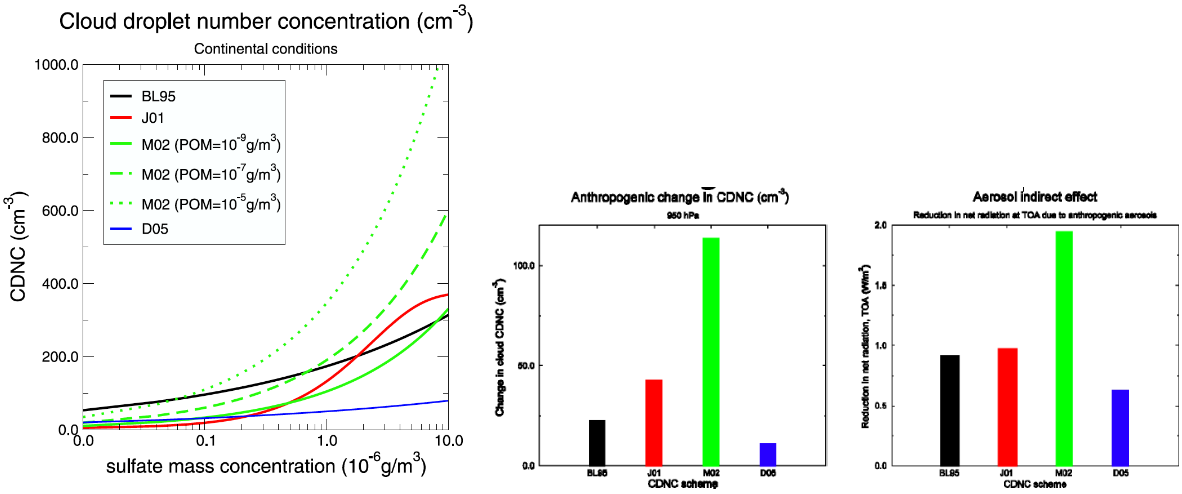

Figure 1: Different empirical relationships used to obtain CDNC from sulfate aerosol mass (left panel), change in CDNC at 950 hPa due to anthropogenic emissions (middle panel) and RFaci (right panel) (Storelvmo et al., 2009).

Murphy et al. (2009) examined the Earth's energy balance since 1950 using only measurements and radiative transfer models. With this method they obtained the ocean heat content and RF by long-lived greenhouse gases and volcanic eruptions. The residual can then be attributed to AFari+aci, adjustments caused by greenhouse gases and any other unknown mechanisms. Assuming that the residual is dominated by AFari+aci provides a so-called inverse estimate of AFari+aci of -1.1 W m^{-2} with a range between -0.7 and -1.5 W m^{-2}. Comparing this range to the AFari+aci from the GCMs in AR4 showed that the range from GCMs clearly exceeds the range that would be consistent with observations. A similar conclusion was already reached by Anderson et al. (2003).

3 Reasons for overestimating AFari+aci

There are several reasons why GCMs (still) tend to overestimate AFari+aci. GCMs that take fast adjustments into account, do that by using parameterizations for the autoconversion rate that depends on the liquid water content to some power and inversely on CDNC to some other power. This slows down the rain formation when anthropogenic aerosols are considered in addition to natural aerosols and cause the warm clouds in the present-day climate to be longer lived than in pre-industrial times. This so-called cloud lifetime effect was first hypothesized for boundary layer clouds by Albrecht (1989). As an average over 9 GCMs this cloud lifetime effect caused an adjusted forcing of -0.7 W m^{-2} (Lohmann and Feichter, 2005). However, when the lifetime of shallow cumulus clouds is analyzed using a 2D single cloud model and a 3D large-eddy simulation (LES) model, no increase or even a decrease in the lifetime of individual clouds was found (Jiang et al., 2006). This was attributed to an evaporation-entrainment feedback, because clouds with more but smaller droplets as found in polluted regions tend to evaporate more readily causing higher cloud-top entrainment, which counteracts the decrease in the collision-coalescence rate. Cloud-top entrainment in GCMs is either not parameterized or rather crudely represented and thus cannot balance the suppressed autoconversion rate.

The overestimation of the so-called cloud lifetime effect in GCMs is partly due to the fact that GCMs put too much emphasis on the autoconversion rate. As shown in Posselt and Lohmann (2009), 40% of the rain in the ECHAM5 GCM is formed by autoconversion if rain is treated diagnostically, which is the standard approach in most GCMs. If rain is treated prognostically, then the importance of autoconversion in the rain formation process is decreased to less than 10% in better agreement with observations

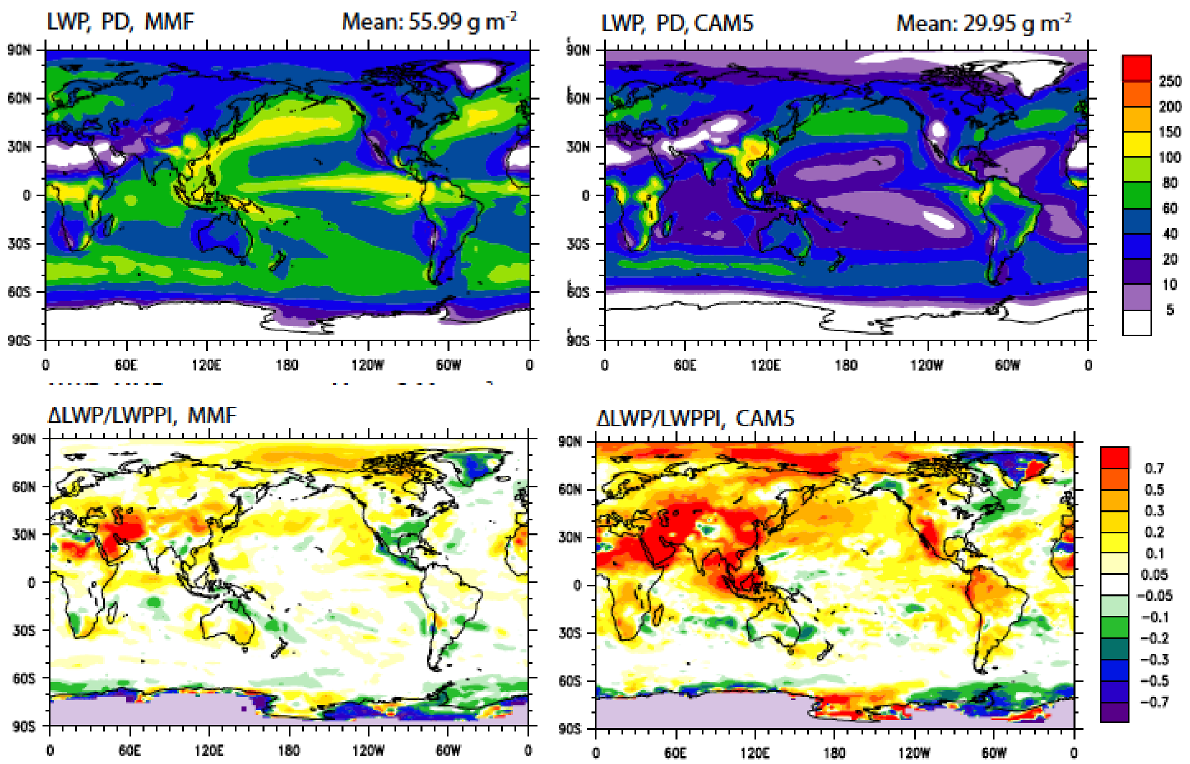

Figure 2: Liquid water path (LWP) in the present-day climate (upper row) and the fractional change in LWP since pre-industrial times (lower row) using the multi-scale modeling framework (MMF) approach (left column) and the CAM5 GCM (right column) (Wang et al., 2011).

(Wood, 2005). Prognostic rain as an additional variable was also proposed in the working group on parameterization of cloud microphysical processes in this workshop (see their report) even if it requires sub-time-stepping and with that a considerable increase in CPU time, because it better represents the warm rain process and better captures the evaporation of rain below cloud base. In the context of anthropogenic aerosol effects, prognostic rain reduces AFari+aci by 0.5-0.9 W m^{-2} in the ECHAM5 GCM depending on the shape of the rain drop distribution (Posselt and Lohmann, 2009).

Another example for important missing processes is given in Wang et al. (2011). They compared AFaci using the CAM5 GCM and the multi-scale modeling framework (MMF) approach, in which a 2D cloud-resolving model (CRM) is embedded in each vertical column of the GCM grid. The CRM replaces the large-scale and convective parameterization as well as the turbulence and boundary layer scheme. Due to the better representation of the aerosol-cloud interactions in the CRM, AFari+aci is reduced from -1.66 W m^{-2} in the CAM5 GCM to -1.05 W m^{-2} using the MMF approach. This can be attributed to the smaller fractional increase in liquid water path (LWP) since pre-industrial times as shown in Figure 2. One the one hand, LWP from stratiform in CAM5 is rather low in the present-day climate with only 30 g m^{-2} whereas satellite data suggest a range between 50-87 g m^{-2} (Wang et al., 2011) and on the other hand its fractional increase is four times higher in CAM5 than in the MMF framework. This higher fractional change that exceeds 30% in large parts of the Northern Hemisphere (Figure 2) together with a slightly larger fractional increase in the cloud condensation nuclei concentration causes the more negative AFari+aci.

The summary plot of RFaci, AFaci, AFari+aci (Figure 3) shows a large spread in AFari+aci estimates if aerosol-cloud interactions in mixed-phase clouds are considered. In this category the AFari+aci estimates range between -0.3 W m^{-2} and -2.5 W m^{-2}, suggesting that aerosol effects on mixed-phase clouds exist that partly compensate aerosol effects on warm clouds. One of these effects has been referred to as the glaciation effect (Lohmann, 2002). It refers to an increase in ice nuclei (IN) from pre-industrial to present-day times which results in a faster glaciation of supercooled clouds, which in turn increases the precipitation rate via the ice phase and increases the scavenging of aerosols, thus decreasing AFari+aci. The large uncertainty associated with the glaciation effect is that it is not clear if IN are indeed increasing due to anthropogenic activities or if on the contrary fewer of them are available due to being mixed with or coated by soluble anthropogenic material as suggested by newer studies (Hoose et al., 008b; Storelvmo et al., 2008). If a mixed-phase clouds glaciates or not, strongly depends on the Bergeron-Findeisen process. If a more physical parameterization of this process, that takes the subgrid-scale variability of the vertical velocity into account, is applied, AFari+aci is reduced by 0.7 W m^{-2} in the CAM-Oslo GCM (Storelvmo et al., 2008, 2010) and by 0.3 W m^{-2} in the ECHAM5 GCM (Lohmann and Hoose, 2009). This example illustrates that a better representation of the dynamical processes can have an important influence on AFari+aci.

4 Aerosol effects on cirrus clouds

Much less in known about aerosol effects in cirrus clouds, because fewer in-situ studies as for warm clouds exist and fewer GCMs tried to estimate RFaci/AFaci for cirrus clouds. The two studies that exist (Penner et al., 2009) and (Gettelman et al., 2012) come to contrary conclusions. The study by Penner et al. (2009) predicts an RFaci of -0.5 to -0.7 W m^{-2} caused by the overall decrease in ice crystal number concentration in the present-day. The reduced ice crystal number causes a positive shortwave forcing that is over-compensated by a negative longwave forcing in case of optical thin cirrus clouds. On the contrary Gettelman et al. (2012) predict a positive AFaci in cirrus clouds between 0.2 and 0.4 W m^{-2} due to more ice crystals in the present-day climate. Thus even the sign of aerosol effects in cirrus clouds is not yet known.

The adjusted forcing due to aerosol-radiation and aerosol-cloud interactions (AFari+aci) as estimated from GCMs that mainly consider first-order processes remains to be uncertain and amounts to -1.6 W m^{-2} (Figure 3). However, if secondary processes, such as subgrid-scale variability in the Bergeron-Findeisen process or prognostic rain that places more emphasis on the accretion process are accounted for in GCMs, AFari+aci becomes smaller in better agreement with the results from the MMF approach (Wang et al., 2011) or the observationally based inverse estimate of AFari+aci by Murphy et al. (2009). This would also explain why AFari+aci is smallest of satellite data are used to for its estimates, because then these missing secondary processes are accounted for in an ad-hoc way.

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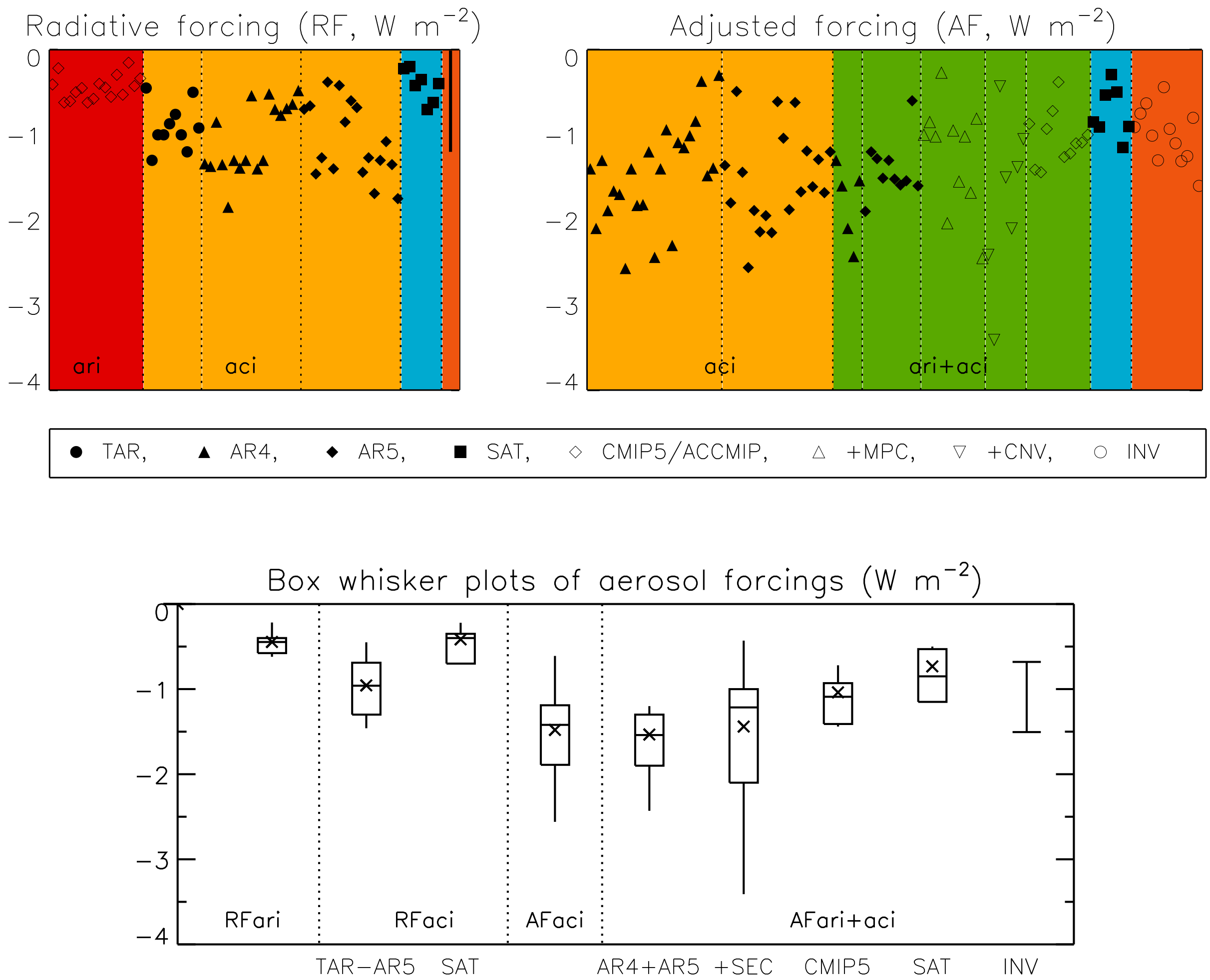

Figure 3: Upper panel: GCM, satellite and inverse estimates of RFari, RFaci, AFaci and AFari+aci. Each symbol represents the best estimate per model and paper. The RFaci studies are divided into those from GCMs published prior to TAR, AR4 and AR5, those including satellite data (SAT) and the inverse estimate (INV). AFaci and AFari+aci studies from GCMs on liquid stratiform clouds are also divided into those published prior to AR4 and AR5 and from the CMIP5/ACCMIP models. GCM estimates that include adjustments beyond aci in liquid stratiform clouds are marked +MPC when including aci in mixed-phase clouds and are marked +CNV when including aci in convective clouds. For RFaci from inverse estimates the range instead of the best estimate is given because it is only one study.
Lower panel: Box whisker plots of GCM, satellite and inverse estimates of RFari, RFaci, AFaci and AFari+aci. They are grouped into RFari from CMIP5/ACCMIP GCMs, RFaci from GCMs (TAR, AR4, AR5) and satellites (SAT), AFaci from GCMs, AFari+aci from GCMs taking aci only on liquid stratiform clouds (AR4+AR5) and including secondary processes (aci on mixed-phase or convective clouds) into account (+SEC), AFari+aci studies from the CMIP5 models, satellites (SAT) and inverse estimates of AFari+aci. Displayed are the averages (cross sign), median values (middle line), 33% and 67% percentiles (box boundaries) and 5% and 95% percentiles (ends of vertical lines) except for the inverse estimates, which is an expert assessment of the combined estimate of multiple inverse estimates. The figure is a updated and improved version of what was provided in Lohmann et al. (2010).

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