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Interpreting the cloud cover – aerosol optical depth relationship found in satellite data using a general circulation model

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Abstract

Statistical analysis of satellite data shows a positive correlation between aerosol optical depth (AOD) and total cloud cover (TCC). Here we compare the slope of the linear regression between the logarithm of TCC and the logarithm of AOD, or the strength of the relationship, as derived from three satellite data sets to the ones simulated by a global aerosol-climate model. We analyze model results from two different simulations with and without a parameterization of aerosol indirect effects, and using dry compared to humidified AOD. We find that none of the hypotheses discussed in the literature is able to uniquely explain the positive relationship. The most important contribution in the model is from the swelling of aerosol in the vicinity of clouds, where relative humidity is high. The model also shows contribution of the aerosol cloud lifetime effect to the positive relationship, which, however, is of lesser importance.

1 Introduction

Aerosols can impact clouds by serving as cloud condensation nuclei (CCN). Since some aerosols and aerosol precursor gases are emitted by anthropogenic activities, this implies an anthropogenic perturbation of the climate system (Lohmann and Feichter, 2005; IPCC, 2007). At higher aerosol concentrations, cloud droplet number concentration (CDNC) is generally increased, which leads to increased cloud albedo for constant liquid water path (Twomey, 1974). Cloud microphysics and dynamics may also respond to changes in aerosol concentration. It has been postulated that when droplet sizes are reduced due to increased CDNC, precipitation formation processes might be delayed, so that cloud lifetime and subsequently total cloud cover (TCC) is increased (Albrecht, 1989).

Satellite data show indeed a positive correlation between TCC and aerosol optical depth (AOD), a measure of vertically integrated light extinction by aerosol (Sekiguchi et al., 2003; Loeb and Manalo-Smith, 2005; Kaufman et al., 2005a; Kaufman and

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Koren, 2006; Matheson et al., 2006; Myhre et al., 2007; Menon et al., 2008; Quaas et al., 2008). Interpreting this relationship, it has been suggested that global annual mean cloud cover increased by 3% due to anthropogenic aerosol (Kaufman and Koren, 2006). Such an effect would introduce a very large radiative forcing, which would almost be sufficient to balance the forcing by a doubling in CO2 concentration (Slingo, 1990).

However, it is largely debated in the recent literature whether the satellite-derived TCC-AOD relationship is due to the aerosol cloud lifetime effect, or whether it could be explained by other reasons. There are mainly six hypotheses discussed

1. Cloud lifetime effect: Aerosols act as CCN increasing CDNC and decreasing droplet size. This may delay precipitation formation and may subsequently increase cloud lifetime and TCC (Albrecht, 1989; Kaufman and Koren, 2006). The TCC-AOD relationship is explained as causality with aerosols influencing TCC through microphysical processes.

2. Meteorological co-variation: In meteorological situations such as large-scale convergence, increased aerosol number concentrations occur at the same time and location as larger TCC (Mauger and Norris, 2007; Loeb and Schuster, 2008).

3. Aerosol swelling: Aerosol size increases in the air surrounding clouds where relative humidity is higher (Haywood et al., 1997; Charlson et al., 2007; Koren et al., 2007; Myhre et al., 2007; Twohy et al., 2009). In contrast to hypothesis 2, the actual aerosol number concentration is not increased, but just the AOD, the metric used to quantify it, is larger.

4. Satellite retrieval errors: Scattering of sunlight at sides of clouds with complex shapes increases reflected radiation in the vicinity of clouds, which results in a high-bias in the retrieved AOD near clouds ("3-D radiation bias"; Loeb and Manalo-Smith, 2005; Wen et al., 2007; Várnai and Marshak, 2009). Also, spurious clouds might be un-detected by the retrieval algorithm in regions identified as

clear and thus used for an AOD retrieval ("cloud contamination"; Kaufman et al., 2005b; Zhang et al., 2005; Tian et al., 2008). In both cases, AOD is high-biased in the vicinity of clouds. However, airborne high-spectral resolution lidar data, unbiased by such artifacts, also show an increase in aerosol scattering in the vicinity of clouds (Su et al., 2008), as do spaceborne lidar data (Tackett and Di Girolamo, 2009).

5. Cloud processing or in-cloud nucleation of aerosols: Inside cloud droplets, aqueous sulfur chemical reactions lead to sulfate formation. This process together with collision-coalescence processes support the growth of embedded CCN upon the evaporation of cloud droplets, potentially enhancing AOD (e.g., Feichter et al., 1996; Su et al., 2008)

6. Wet scavenging: Wet scavenging of aerosol by precipitation formed in clouds, the predominant sink of CCN, would introduce a relationship between AOD and cloud cover, which, however, presumably would be negative.

In the present study, we examine the relative importance of these hypotheses with the help of general circulation model (GCM) sensitivity studies.

2 Methods

The satellite data used here are from the MODerate Resolution Imaging Spectroradiometer (MODIS; Minnis et al., 2003; Remer et al., 2005) on board the Terra and Aqua satellites, as obtained from the Clouds and the Earth's Radiant Energy System (CERES; Wielicki et al., 1996) SSF Edition 2 datasets. Terra data, valid for about 10:30 a.m. local time, cover the January 2001–December 2007 period, and Aqua data, with 1:30 p.m. local overpass time, the January 2004–December 2006 period. Also used are data from the Along-Track Scanning Radiometer (ATSR-2) on board the ERS-2 satellite with an equator-crossing local time of about 10:30 a.m. from the

Oxford-RAL Aerosols and Clouds (ORAC) Global Retrieval of ATSR Cloud Parameters and Evaluation (GRAPE; version 3; Thomas et al., 2009; Poulsen et al., 2009) for the January 1996–December 1999 period. It should be noted that the MODIS retrievals are done at a $10\times10\,km^2$ grid, while the ATSR-2 retrievals are performed at a somewhat higher resolution of $3\times4\,km^2$.

The atmospheric GCM used is the ECHAM5 model (Roeckner et al., 2003), coupled to the modal aerosol scheme HAM considering sea salt, dust, sulfate, black carbon and organic carbon in seven internally mixed hydrophilic or hydrophobic log-normal modes with fixed variance, including aerosol microphysical interactions (Stier et al., 2005). The model is run at T63L31 resolution for one year with prescribed monthly-mean AMIP2 sea surface temperature and sea-ice cover distributions for AD 2000, with aerosol and aerosol precursor emissions from the AEROCOM dataset valid for the year AD 2000 (Dentener et al., 2006). The cloud cover and large-scale condensation are diagnosed from a prognostic subgrid-scale distribution of total water mixing ratio (Tompkins, 2002). In this scheme, cloud cover is not prognostic. Nevertheless, due to its flexibility, the scheme is likely to be relatively sensitive in terms of cloud cover to perturbations as, e.g., by the second aerosol indirect effect (Lohmann and Feichter, 1997; Lohmann et al., 2007). ECHAM5 includes two different choices for cloud microphysical schemes. The standard single-moment cloud scheme treats liquid and ice water mixing ratio as prognostic variables, but does not consider aerosol influences on cloud microphysics (Lohmann and Roeckner, 1996). The optional double-moment liquid and ice-cloud microphysical scheme (Lohmann et al., 2007) parameterises droplet activation following the empirical formulation by Lin and Leaitch (1997), and applies the autoconversion parameterisation by Khairoutdinov and Kogan (2000). In this study, two model integrations are done; one with the single-moment cloud scheme (no aerosol indirect effects included) and one with the double-moment cloud scheme (all parameterized aerosol-cloud interactions included).

Following Feingold et al. (2003), the strength of the aerosol-cloud cover relationship is quantified here as the slope of the linear regression between the natural logarithm of TCC and the natural logarithm of AOD

$$b = \Delta \ln \mathrm{TCC} / \Delta \ln \mathrm{AOD}.$$

This quantity shows the relative change in TCC with a relative perturbation in AOD.

We compute the regressions for both, satellite data and GCM simulation results, in a consistent way, gridding the satellite data to the model grid, separately for fourteen different ocean and land regions and the four seasons as in Quaas et al. (2008). The geographical distribution of the regions is shown in Supplementary Fig. 1 (http://www.atmos-chem-phys-discuss.net/9/26013/2009/acpd-9-26013-2009-supplement.zip). Spatial scale plays an important role when computing statistical relationships. We assure comparability here by interpolating all data to the model's T63 horizontal grid (approx. 1.8° resolution).

3 Results and discussion

Figure 1 shows the slopes of the regression between TCC and AOD as the weighted mean values for ocean and land areas for all seasons, with the error bars showing the variability among the regions and seasons as standard deviation. For the satellite datasets, the intra-annual variability is also included in the computation of the standard deviation shown in the error bars. All individual sensitivities are shown in Supplementary Fig. 2 (http://www.atmos-chem-phys-discuss.net/9/26013/2009/acpd-9-26013-2009-supplement.zip).

As previously reported, the MODIS data show a strongly positive relationship between TCC and AOD. There is no clear land-ocean contrast, and a substantial variability among the regions/seasons and even between the years (note that for MODIS on Terra, we had eight years of data available compared to only three for MODIS on Aqua). There is no distinct seasonal cycle in this strength, nor are differences between the

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hemispheres, or between tropics and extratropics evident. The most prominent feature is a land-ocean contrast with some land regions showing quite large, others smaller values than the more homogeneous oceanic regions. The ATSR2 dataset also shows a positive relationship. The ATSR2-derived slope is on average similar to the MODIS Terra slope over the oceans, but much smaller over land. ATSR2 shows much more variability, and the small value over land is dominated by negative correlations over Africa and Oceania (Supplementary Fig. 2c, http://www.atmos-chem-phys-discuss.net/9/26013/2009/acpd-9-26013-2009-supplement.zip), where the influence of large dust loading, and related retrieval issues, may play a role.

ECHAM5-HAM in the control simulation shows relationship strengths smaller than in the reference satellite data by about 50%, of the order of 0.1. In the second model study, the single-moment cloud microphysical scheme is used. In this scheme, aerosols do not influence cloud microphysics – aerosol indirect effects are switched off. This simulation "NOAIE" nevertheless shows a strongly positive relationship between TCC and AOD, with the slight land-ocean contrast virtually unchanged. However, the strength of the relationship is reduced. The amount by which the relationship is less strong in the simulation without the aerosol indirect effects compared to the control simulation might indicate the relative contribution of the simulated cloud lifetime effect to the positive relationship between TCC and AOD. However, this conclusion has to be treated with caution since the model versions are different (one- versus two-moment cloud microphysical scheme), and the parameterization of the cloud lifetime effect just in terms of the autoconversion parameterization is crude. On the other hand, the cloud lifetime effect may be overestimated in the model rather than underestimated (Quaas et al., 2009). The result found here is consistent with the findings of Lohmann et al. (2006), who investigated the vertically resolved TCC for four bins of AOD over the tropical Atlantic ocean.

We further analyse the results of the latter simulation (NOAIE) using two different ways to compute AOD. In one case, we use the dry masses of all aerosol species to compute the AOD ("DRYAOD"), and in a second case, only the dry mass concentrations of the aerosol species considered good cloud condensation nuclei ("DRYSOLUBLE"), namely sea salt, sulfate and organic carbon. The optical depth by aerosol components (dry aerosol species and aerosol water) is estimated from the total aerosol optical depth as the component volume fraction of the total AOD.

It is evident that in the ECHAM5-HAM model, the aerosol water uptake is responsible for much of the relationship between TCC and AOD. Indeed, when using the dry aerosol mass to compute the relationship, it becomes negative rather than positive. A negative relationship is what would be expected if the aerosol sink by wet scavenging was the dominant process which relates cloud cover and aerosol concentration. This negative relationship between TCC and AOD is virtually unchanged when the dry mass concentration only of potential CCN (soluble particles) is used. This suggests that the large dust concentrations in particularly dry areas, and thus a purely geographical correlation, is not the main factor by which the negative relationship between TCC and dry AOD is influenced.

4 Summary and conclusions

Reasons for the strongly positive relationship between total cloud cover (TCC) and aerosol optical depth (AOD) as found in satellite datasets are explored using sensitivity studies with a general circulation model (the ECHAM5 GCM) including the comprehensive aerosol module HAM and the choice for either a double- or a single moment cloud microphysical scheme. Six hypotheses have been identified in the literature which might explain the correlation between cloud cover and aerosols (see Introduction): (1) The cloud lifetime aerosol effect, (2) meteorological co-variation, (3) aerosol swelling in the humid environment where clouds form, (4) satellite retrieval errors, (5) in-cloud aerosol production and processing, and (6) aerosol wet scavenging, where the latter effect would produce a negative rather than positive relationship. All effects, except for satellite retrieval errors, are represented or parameterized in the model. Under the (most likely overly optimistic) assumption that these representations are correct, the extent to which the model shows a less strong relationship between TCC and AOD infers the amount by which satellite retrieval errors (hypothesis 4) are responsible for the positive relationship found in the satellite data. Interestingly, we find in the MODIS datasets a much stronger relationship than in the model control simulation.

The model shows a slope about 40% lower over land and about 50% lower over ocean in the case where aerosol indirect effects are switched off. An interpretation would be that in the model, a considerable part of the correlation between TCC and AOD is due to impacts of aerosols on cloud microphysics (hypothesis 1).

A very strong signal is obtained when using AOD computed from the dry aerosol mass concentrations rather than humidified aerosol. The relationship between TCC and AOD turns strongly negative in this case. It is not a pure geographical co-variation as shown when using the dry AOD computed only from the soluble aerosol components. Rather, the wet scavenging of aerosol by precipitation formed in clouds is likely an important process determining this negative relationship. The difference in the relationship between TCC and humid AOD and TCC and dry AOD, respectively, clearly shows that the influence of high humidity in the vicinity of clouds causes a swelling of the existing aerosol increasing the AOD (hypothesis 3). In-cloud aerosol production and aerosol microphysical processing (hypothesis 5), as well as meteorological co-variation (hypothesis 2) are both included in this relationship, but seemingly do not play a large role. However, we could not disentangle these latter three processes.

In agreement with findings by Myhre et al. (2007) and Twohy et al. (2009), our results suggest that the humidification of aerosol in the vicinity of clouds is the dominant process (process 3 in the above list) contributing to the observed strong correlation between TCC and AOD in remote sensing data, followed by the cloud lifetime effect (process 1). However, satellite retrieval errors are potentially quite important at least in some (here the MODIS) satellite datasets (process 4). All other effects are likely of lesser importance.

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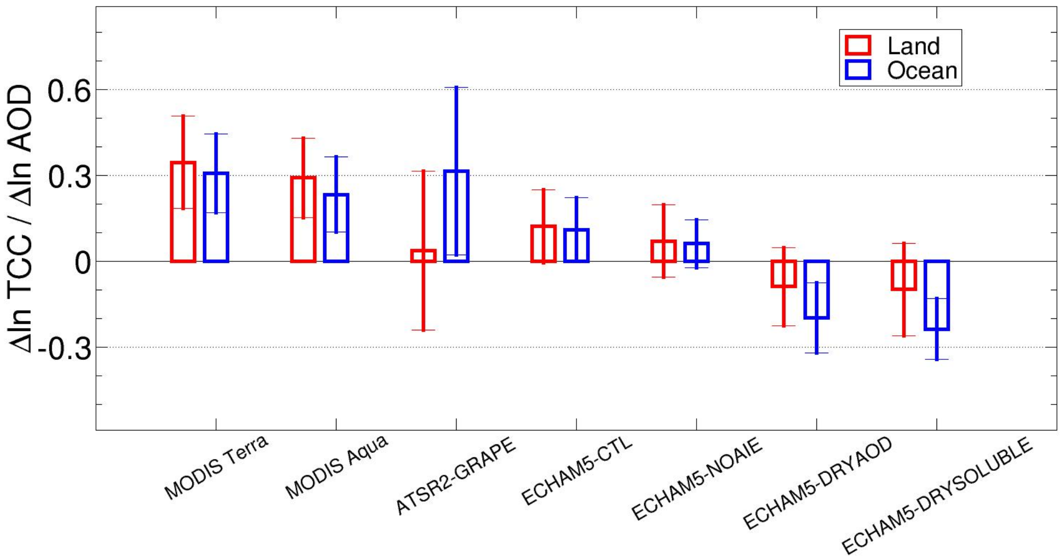

Fig. 1. Slope of the relationship ln TCC vs. ln AOD (see text for details). The weighted average for four seasons and all six land regions (red) and eight ocean regions (blue) is shown, with the variability as error bar. Error bars for the satellite data also include the inter-annual variability among the eight, three and four years, for MODIS Terra, MODIS Aqua, and ATSR2-GRAPE, respectively.

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