An Examination of the Effects of Aerosols on the Reflected Radiation by Clouds

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Introduction

Atmospheric aerosols affect the radiation balance at the surface and at the top of the earth's atmosphere. They directly scatter and absorb radiation, yet the aerosol particles indirectly affect the radiation budget because they act as cloud condensation nuclei (CCN). This changes the optical properties of the cloud. For example, an increase in aerosols increases the number of CCN. This may lead to higher cloud droplet number concentrations and a higher cloud reflectivity.

The two mechanisms are called the direct and indirect effect of aerosols on clouds. Both effects provide a negative radiative forcing and therefore tend to cool the atmosphere. However, the magnitude of the aerosol effects on the climate system and, in particular, the magnitude of the indirect effect of aerosols on clouds are still uncertain and under ongoing investigation. Model calculations suggest that the net radiative forcing lies in the range of -0.5 W/m^2 to -3 W/m^2.

The goal of this project is to gain a better understanding of the indirect effect of aerosols on clouds. This contributes to a better representation of aerosol and cloud properties in general circulation models. To accomplish this goal, we examine the indirect effect using a cloud-aerosol parameterization developed by Chuang et al. (1997). This parameterization is based on a mechanistic approach to parameterizing the aerosol effects on the cloud droplet number concentration. In order to test the parameterization we use Atmospheric Radiation Measurement (ARM) Program data sets collected at the Southern Great Plains (SGP) site in Oklahoma (central facility) in recent years. This site offers a great variety of different measurements we use to apply the cloud-aerosol parameterization and to derive initial conditions for a radiative transfer model. The results of the radiative transfer calculations are then examined with respect to the aerosol indirect effect.

ARM Measurements and Data Analysis Method

The cloud-aerosol parameterization is tested using simultaneous measurements of five different instruments operated at the ARM SGP site. In particular, we combine radiosonde data (BBSS), ceilometer data (BLC), microwave radiometer data (MWR), aerosol measurements (AOS) and satellite data (GOES-8) to collect information on the vertical pressure, temperature, and relative humidity (cloud base and top) profiles (BBSS), on the height of the cloud base (BLC), and on the cloud liquid water path (MWR). In addition, the ground-based aerosol observation system (AOS) provides data on the total aerosol number concentration (condensation nuclei counter, CN) and the actual aerosol size distribution in different size bins (optical particle counter, OPC). Here, the optical particle counter measures 31 size bins within the diameter range 0.1 μm to 10 μm, whereas the condensation nuclei counter includes a wider size range (0.01 μm to 10 μm). Satellite measurements are used to examine the total cloud cover, the albedo, the solar zenith angle, and the reflected shortwave narrow and broadband radiation over the SGP site.

The data analysis consists of three steps.

1. First, the aerosol-cloud parameterization according to Chuang et al (1997) and Ghan et al. (1993) is applied. Here, the cloud droplet number concentration N_d is predicted by $N_d = w*N_a / (w + c*N_a)$ where w stands for the vertical updraft velocity within the cloud. Because no measured data of the updraft are available, the vertical velocity is assumed to be 25 cm/s, which is typical of stratiform clouds. N_a denotes the total aerosol number concentration measured at the ground by the condensation nuclei counter. Typical values are several thousand particles per cm^3. The parameter c was derived from a microphysical model and is represented by $c = 0.04095 + 21.587*X_L$ where X_L depends on the sulfate mass loading, aerosol concentration N_a, and vertical velocity w (details in Chuang et al. 1997). Once drop concentrations N_d at cloud base due to supersaturation (activated aerosols) are established, they remain nearly constant with altitude at least in the early stages of a stratiform cloud.

2. Second, the predicted cloud droplet number concentration and the measured data sets serve as input data for a radiative transfer model. This radiation code (developed by Keith Grant, Lawrence Livermore National Laboratory) calculates the reflected radiation at the top of the atmosphere (TOA), which is compared to the GOES-8 satellite observations. Furthermore, the model analyzes the cloud optical depth τ.

3. Finally, the indirect effect of aerosols is assessed. For an adiabatic cloud, the indirect effect of aerosols on the cloud droplet number concentration can be examined by plotting $\tau/H^{5/3}$ versus $N_d^{1/3}$. Here, τ stands for the (modeled) cloud optical depth, H denotes the (measured) cloud geometrical thickness, and N_d symbolizes the (predicted) cloud droplet number concentration. This theoretical relationship has been experimentally confirmed in field studies on the Canary Islands, which represent a maritime environment (Brenguier et al. 2000). Figure 1 (Brenguier et al. 2000) shows the dependencies between τ, H, and N_d. Although the data are scattered significantly (e.g., due to small errors in H), they still indicate the typical linear trend, which is characteristic for adiabatic clouds. The figures suggest that the optical depth could be proportional to $H^{5/3}$ and $N_d^{1/3}$, which is the basis of the aerosol indirect effect. Here, A^* stands for a normalization factor (approximately $2*10^{-6}$ $m^{-2/3}$, details in Brenguier 2000). Our goal is to confirm this relationship in a continental environment with selected ARM data sets we filter according to specific data selection criteria.

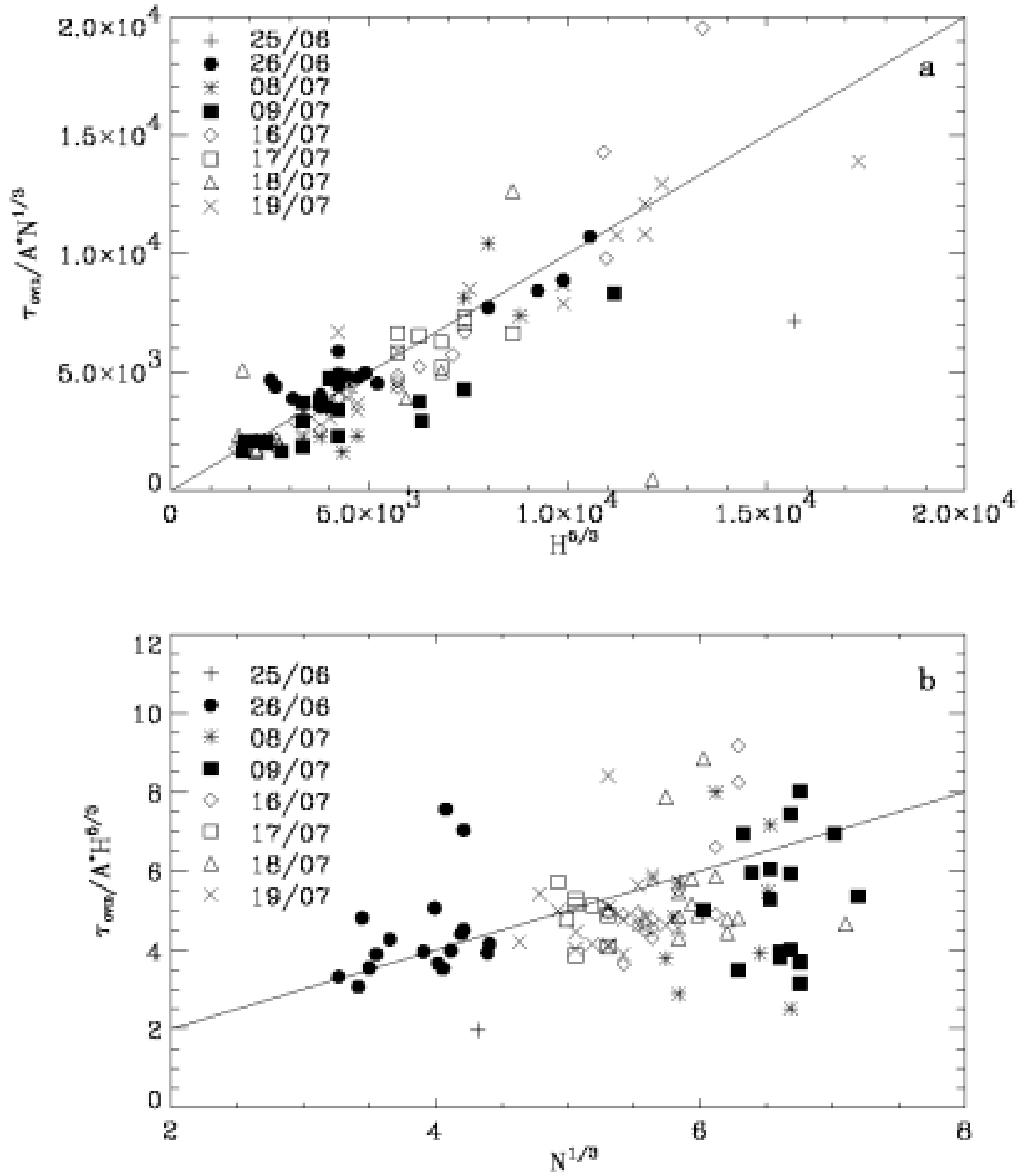

Figure 1. The evaluation of the aerosol indirect effect by Brenguier et al. (2000) shows the relationship between the cloud optical depth τ (remotely sensed), the cloud geometrical depth H, and the cloud droplet number concentration N_d for stratiform, adiabatic cloud systems. H and N_d are based on in situ measurements, A^* is a normalization factor.

Data Selection Criteria

For the test of our parameterization, we consider weather situations that are concurrently characterized as follows:

- Well-mixed boundary layer (BL). Because our aerosol measurements are taken at the ground, we select days with a well-mixed boundary layer. Then the aerosol number concentration at the ground represents the aerosol number concentration near the cloud base. These days are characterized by a nearly constant water vapor mixing ratio below the cloud base.

- Cloud base below 3 km. Because the parameterization is valid for entirely liquid clouds, we pick days with low-level, warm clouds (> -12°C).

- Single, stratiform cloud layer. The satellite provides measurements of the outgoing broadband radiation at TOA. We pick days with single cloud layers and at least 95% cloud cover over the SGP region because these cases clearly correspond to the satellite observations.

- Adiabatic clouds. Our investigation is concentrated on (approximately) adiabatic clouds that have been extensively studied by Brenguier et al. (2000). Adiabatic clouds are characterized by the fact that the water vapor mixing ratio below the cloud base is approximately equal to the sum of the mixing ratio of cloud liquid water and vapor within the cloud.

A typical weather situation that fulfills the selection criteria is presented in Figure 2, which shows the vertical profile of the relative humidity (left) and the water vapor mixing ratio (right). These profiles are based on radiosonde soundings. Here, a single cloud layer is located at around 1 km and the water vapor mixing ratio stays approximately constant below cloud base (within a 10% to 15% range). In addition, the adiabatic assumption is met. An overall comparison of the adiabatic criterion is shown in Figure 3. Here, all data sets are presented that fulfilled the first three selection criteria. The figure provides a comparison of the water vapor mixing ratios below cloud base and the water vapor and liquid water mixing ratios within the cloud. Our subsequent analysis is focused on adiabatic cloud systems. We only select cases where the mixing ratios are nearly equal (within a 10% range).

The different colors and symbols used in the plot indicate the corresponding time period on a monthly basis. Because we only use time periods when data sets from all of the five instruments are available, the analyzed periods are not continuous. The availability of satellite measurements are the most limiting factor.

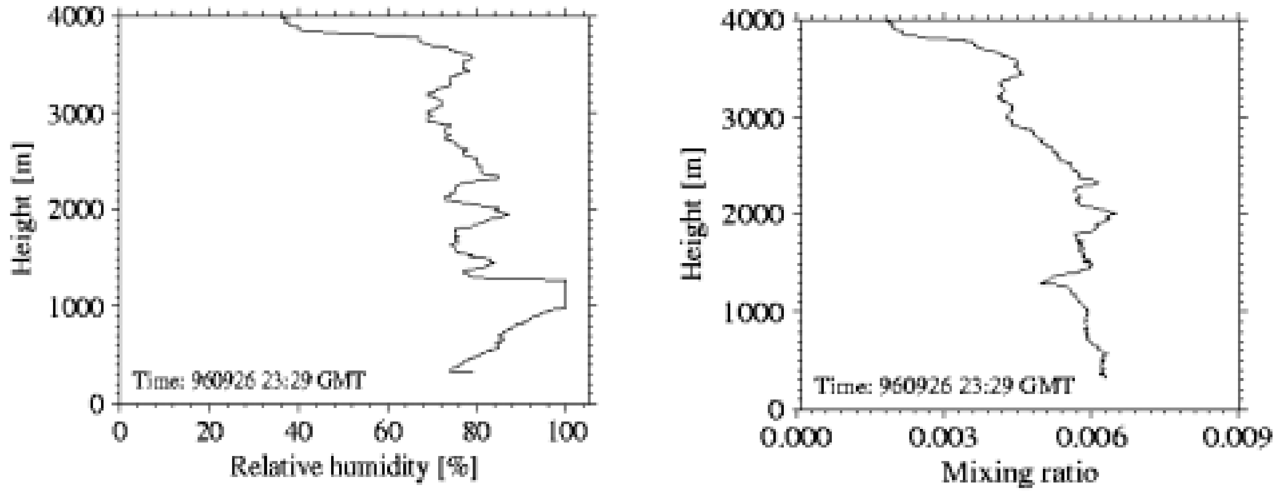

Figure 2. Radiosonde profiles typically selected when applying the selection criteria: relative humidity (left) and water vapor mixing ratio (right).

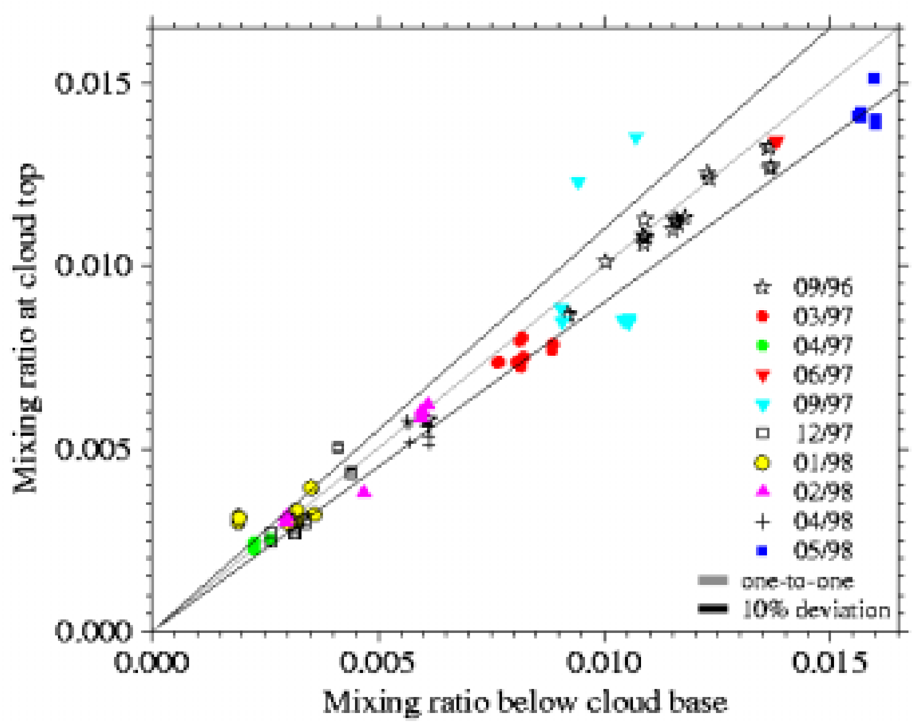

Figure 3. This assessment of the adiabatic assumption shows the comparison of the water vapor mixing ratios below cloud base and the water vapor and liquid water mixing ratios within the cloud. Adiabatic cases lie in between the 10% deviation.

Results

For the tests of our aerosol-cloud parameterization, we examine ARM data sets collected at the SGP site in 1996-1999. All data sets were filtered according to the data selection rules mentioned above. This guarantees that we analyze comparable, representative adiabatic cloud systems. In particular, the adiabatic cloud assumption (constant mixing ratios) is essential for the analysis. In general, it can be found that most of the summer data sets do not fulfill the selection criteria. This reflects the fact that during the summer months most of the cloud systems are convectively driven and therefore show non-adiabatic characteristics.

The selected data sets serve as input data for a radiative transfer code. In particular, the input data incorporate the cloud liquid water path, the overall cloud cover, the cloud base and top (cloud geometrical depth H), the vertical radiosonde profiles, and the predicted cloud droplet number concentration N_d. Here, the information on the cloud top is only derived from the radiosonde's relative humidity profile (a cloud is detected for relative humidities greater than 99%). In contrast, the cloud base is either based on the radiosonde or on the ceilometer information, depending on the data quality. Figure 4 provides insight into the radiosonde - ceilometer intercomparison. It shows the height of the cloud base that is independently measured with the ceilometer (remote sensing technique) and during a radiosonde ascent (criterion: relative humidity exceeds 99%). Note that the ceilometer measures the height of the cloud base several times during one radiosonde ascent (typically two hours). Therefore, the plot contains data sets that appear in lines. This indicates that the cloud boundaries may vary quickly over a two-hour time period and it becomes essential to select points in time that give the best possible agreement among all five instruments.

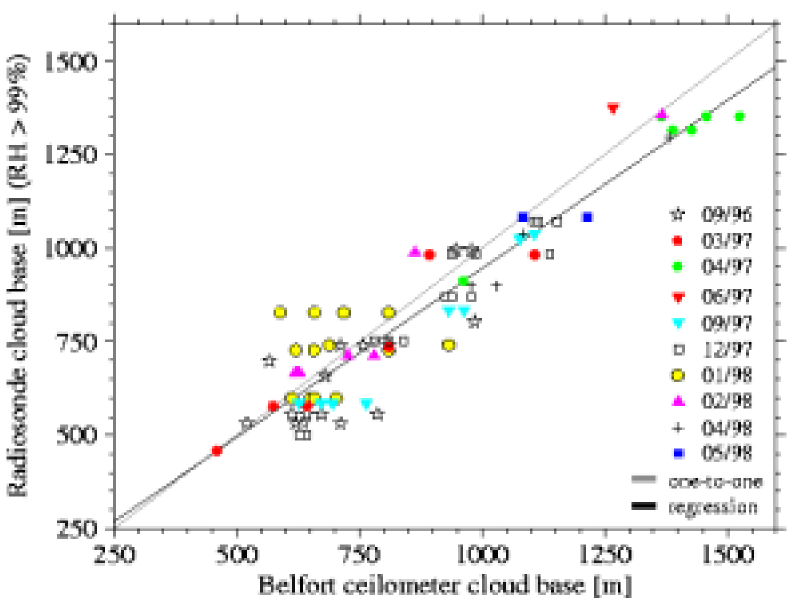

Figure 4. Comparison of the height of the cloud base measured with the ceilometer and during a radiosonde ascent (criterion: relative humidity exceeds 99%). Both measurements indicate the height above mean sea level (the ARM SGP site lies at 315m).

The results of the radiative transfer calculations provide information on the cloud optical depth and reflected shortwave radiation at the TOA. The accuracy of the model calculations can be assessed in Figure 5. It shows the comparison between the measured reflected broadband shortwave radiation (GOES-8) and the modeled reflected radiation at TOA. In addition to the data points, the straight lines indicate the one-to-one line and the results of a regression analysis. In general, the modeled reflected radiation lies close to the measured values. The corresponding correlation coefficient is 0.94. Outlying data points might be related to an inaccurate liquid water path provided by the MWR instrument.

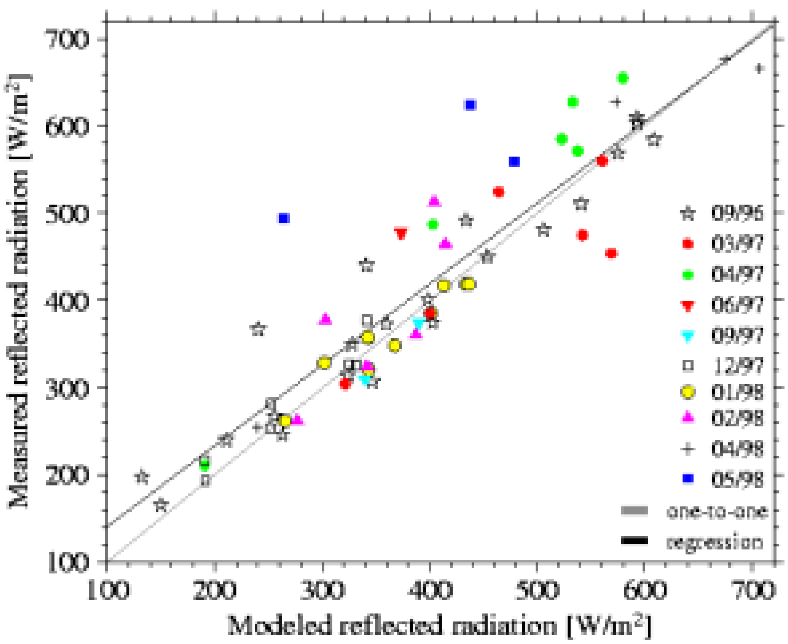

Figure 5. Comparison of the measured reflected broadband shortwave radiation (GOES-8 satellite) and the modeled reflected shortwave radiation at TOA.

The modeled cloud optical depth is then used to examine the indirect effect of the aerosols on clouds. The key question is whether the data sets show a linear relationship that is comparable to the results by Brenguier et al. (2000). Figure 6 presents the corresponding analysis of the ARM data sets that involves the optical depth τ, the geometrical cloud depth H, and the predicted cloud droplet number concentration N_d. No normalization factor A^*, as used by Brenguier et al. (2000), has been applied. It can be seen that the plot is characterized by significant scatter, although the regression seems to suggest a linear trend (with weak correlation). Unlike the analysis of Brenguier et al., it is difficult to see any trend because the data do not span a wide range of values of N_d.

Conclusion

Our current results indicate that the selected ARM data sets show only a weak linear trend when examining the aerosol indirect effect (Figure 6). The clear linear trend noted by Brenguier et al. (2000) during a field study on the Canary Islands (Figure 1) has not been reproduced with ARM data sets yet.

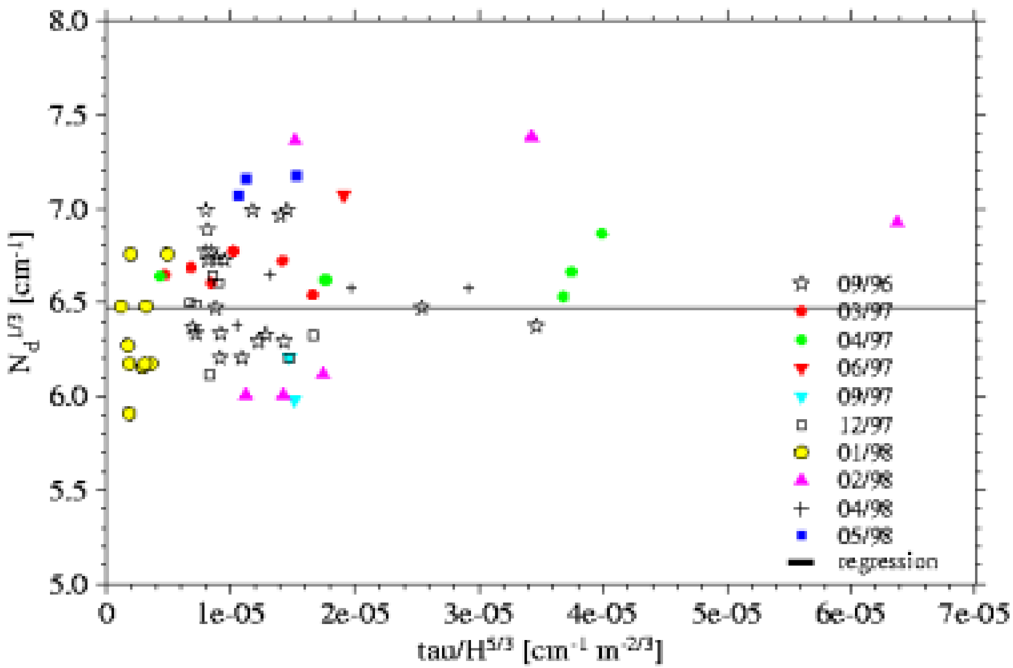

Figure 6. The assessment of the aerosol indirect effect with ARM data sets shows the relationship between the cloud optical depth τ divided by the cloud geometrical depth H (raised to the power 5/3) and the cloud droplet number concentration $N_d^{1/3}$. N_d is predicted using the parameterization by Chuang et al. (1997), H is based on measured data, τ is modeled.

The reasons are possibly related to the inaccuracies when estimating H, the geometrical cloud depth, with combined radiosonde and ceilometer information. Since H is raised to the 5/3 power, small errors in H have a large impact on the analysis. In addition, the assumed vertical velocity introduces errors in the parameterization of the cloud droplet number concentration. In comparison to Brenguier et al. (2000), the predicted range of number concentrations is too narrow. In the future, our hope is to examine a wider set of aerosol conditions by including data from the North Slope of Alaska. Moreover, we hope to also carry out the following steps: (1) in order to better estimate the cloud droplet number concentration, we will use the measured aerosol size distribution information to drive our detailed microphysical model; and (2) we will further improve our estimate of the cloud height H as soon as radar data on the cloud base and top become available. We expect these improvements will reduce the scatter in our current analysis.

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