Quantifying the Aerosol Indirect Effect Using Ground-Based Remote Sensors and Models

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Introduction

The effect of aerosols on cloud microphysical and radiative properties (the "indirect effect") has the greatest uncertainty of all known climate-forcing mechanisms. Increases in aerosol concentrations result in higher concentrations of cloud condensation nuclei (CCN), increased cloud droplet concentrations, and smaller droplet sizes (Twomey 1974). A possible secondary effect is the suppression of rainfall. Together, these effects generate more reflective clouds, which in theory create a radiative forcing estimated on the global scale to range from 0.0 Wm^{-2} to -4.8 Wm^{-2}. Numerous observational studies identify situations where the connection between the aerosol and cloud microphysics is clear, while in other situations no connection appears to exist. However, the conclusions differ widely. For example, some in situ studies identify the indirect effect in stratiform clouds but not in cumuliform. Other studies clearly find the effect in cumuliform clouds. Because the indirect effect is defined as a climatic forcing, it is necessary to extend our scope beyond in situ measurements and evaluate it on the regional or global scale using ground-based or satellite remote sensing. Satellite remote sensing efforts have been widely used in biomass burning regions and provide evidence of the indirect effect beyond the limited environment of ship track or other in situ experiments. However, they also show variation in the strength of the indirect effect that cannot be explained by simple formulations such as Twomey's.

Here we turn to a combination of ground-based observations and theoretical modeling to address these questions. The area of interest is the Southern Great Plains (SGP) Atmospheric Radiation Measurement (ARM) Cloud and Radiation Testbed (CART) site. The advantages of ground-based over satellite remote sensing lie in the type of instrumentation available at SGP. The Raman lidar provides range-resolved measurements of aerosol below clouds (i.e., before they enter cloud and affect cloud microphysics). In contrast, satellites rely on measuring aerosol in cloud-free regions and measuring cloud drop effective radius (r_e) in adjacent cloudy regions; there is no guarantee that the measured aerosol is in fact affecting the cloud.

The primary goals of this work are to:

1. Analyze ground-based remote sensing data to investigate the indirect effect. Previous studies have focused on biomass burning regions where the indirect forcing is usually strong. Here we investigate the indirect effect in a rural, continental site, which is relatively clean compared to biomass burning regions, and experiences only small-scale, intermittent local burning and a few long-range transport events. Typical conditions will be contrasted with the long-range transport of smoke from the Mexican fires (1998) and the New Mexico fires (2000) to SGP.

2. Utilize sophisticated numerical models of aerosol-cloud interaction to examine the underlying physical processes.

3. Explore the reasons for the observed variability in the indirect aerosol forcing using a synthesis of observations, modeling, and some simple theoretical exercises.

Approach

We seek a link between subcloud aerosol (as represented by Raman lidar aerosol extinction, or where applicable, surface aerosol measurements) and the r_e of cloud droplets in nonprecipitating, warm clouds for situations where ancillary observations indicate that the measured aerosol is being transported vertically into the observed cloud. We seek this link for clouds of different types (shallow cumulus and stratiform) different liquid water paths (LWPs), and different levels of aerosol mass loading. The high temporal resolution of the ground-based remote sensors (order of minutes) will enable us to analyze a large data set and address the problem in an empirical manner, with statistical significance.

An illustration of the central idea is given in Figure 1a. Vertical forcing generates a cloud with a LWP. The aerosol, and in particular the CCN, determine the number of cloud droplets, their size distribution n(r), the droplet r_e, and the cloud optical depth τ_d. Figure 1b shows theoretical curves of r_e as a function of the subcloud aerosol extinction α after Feingold et al. (2001). The latter work developed a framework for intercomparison of observed and modeled responses of cloud microphysics to changes in aerosol forcing. The response is formulated as a relative change in r_e for a relative increase in aerosol optical thickness. The slope (power) of these curves and their region of saturation is defined as a measure of the indirect effect.

Derivation of r_e

A number of sources of r_e are being considered. When more than one retrieval is available, intercomparison will yield useful information:

1. Min and Harrison (1996) derive a mean cloud droplet r_e from measurements of cloud LWP and cloud optical depth τ_d, together with a radiative transfer model. Retrieval of r_e is restricted to periods

of single cloud layers because a retrieved r_e for multiple cloud layers has little meaning. Also, it is only possible to retrieve r_e during the day.

2. Frisch et al. (1995) used cloud radar and microwave radiometer to retrieve profiles of r_e in stratocumulus, under the assumption of a constant drop concentration and fixed distribution breadth. Although the retrieval is sensitive to the above assumptions, it does provide a good qualitative measure of r_e. This retrieval is difficult in boundary-layer clouds during the summer months at SGP due to contamination of radar reflectivity by insects. Nevertheless, in the winter, spring, and fall, when insect activity is low, and ice is absent, the Frisch et al. method is being applied. An added advantage is that profiles of r_e can also be measured at night. Figure 2 shows time series of r_e derived by Min and Harrison (1996) with a modified form of the Frisch et al. (1995) algorithm. Instead of deriving drop concentration from the microwave radiometer and radar (which tends to generate a noisy field, particularly in broken clouds), we derive drop number based on the surface concentration of accumulation mode aerosol, provided the boundary layer is well mixed. The r_e is then scaled such that the LWP equals that measured by the microwave radiometer.

3. The Terra (EOS AM-1) satellite overpasses of the SGP site will provide us with Moderate Resolution Imaging Spectroradiometer (MODIS)-derived r_e (or equivalent) that will be a useful comparison with the other methods of deriving r_e. Since MODIS only has a twice-daily overpass of SGP, this method will yield relatively few data points. However, the MODIS community should benefit greatly from comparisons of their retrieved r_e with the other methods.

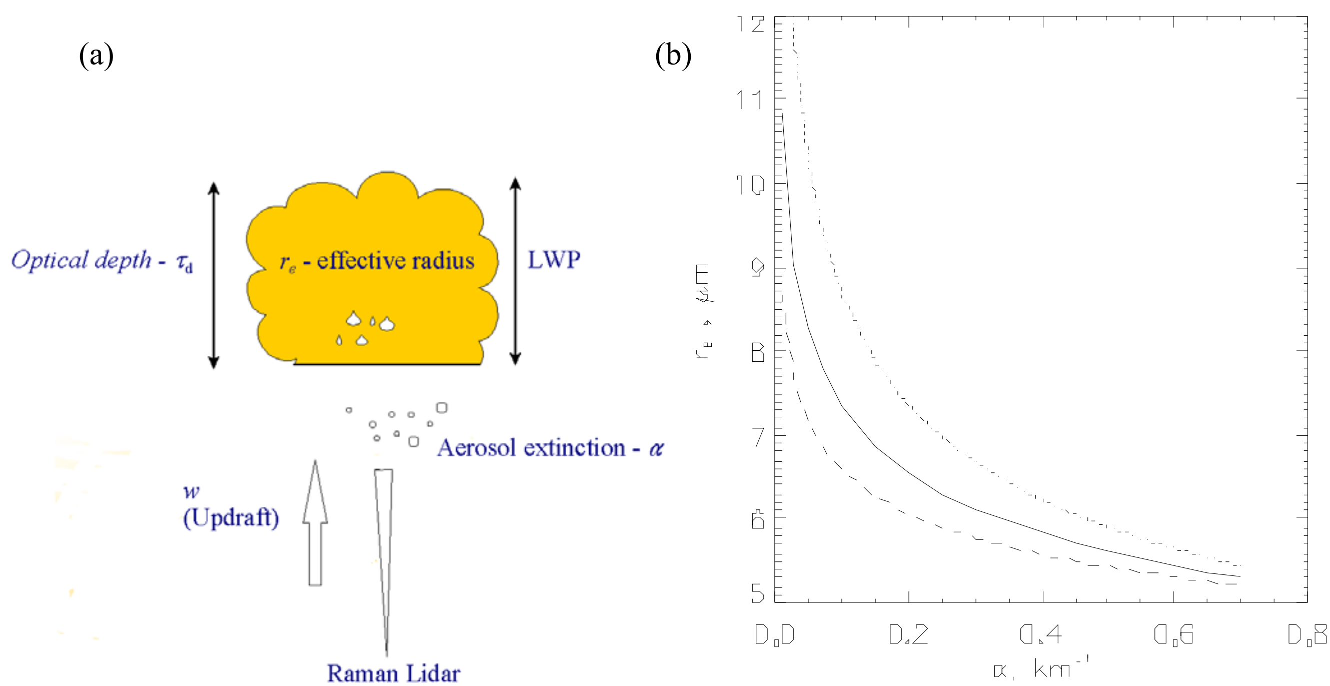

Figure 1. (a) Schematic describing the use of ground-based remote sensors to address the indirect effect. (b) Theoretical curves showing r_e as a function of aerosol extinction α (after Feingold et al. 2001).

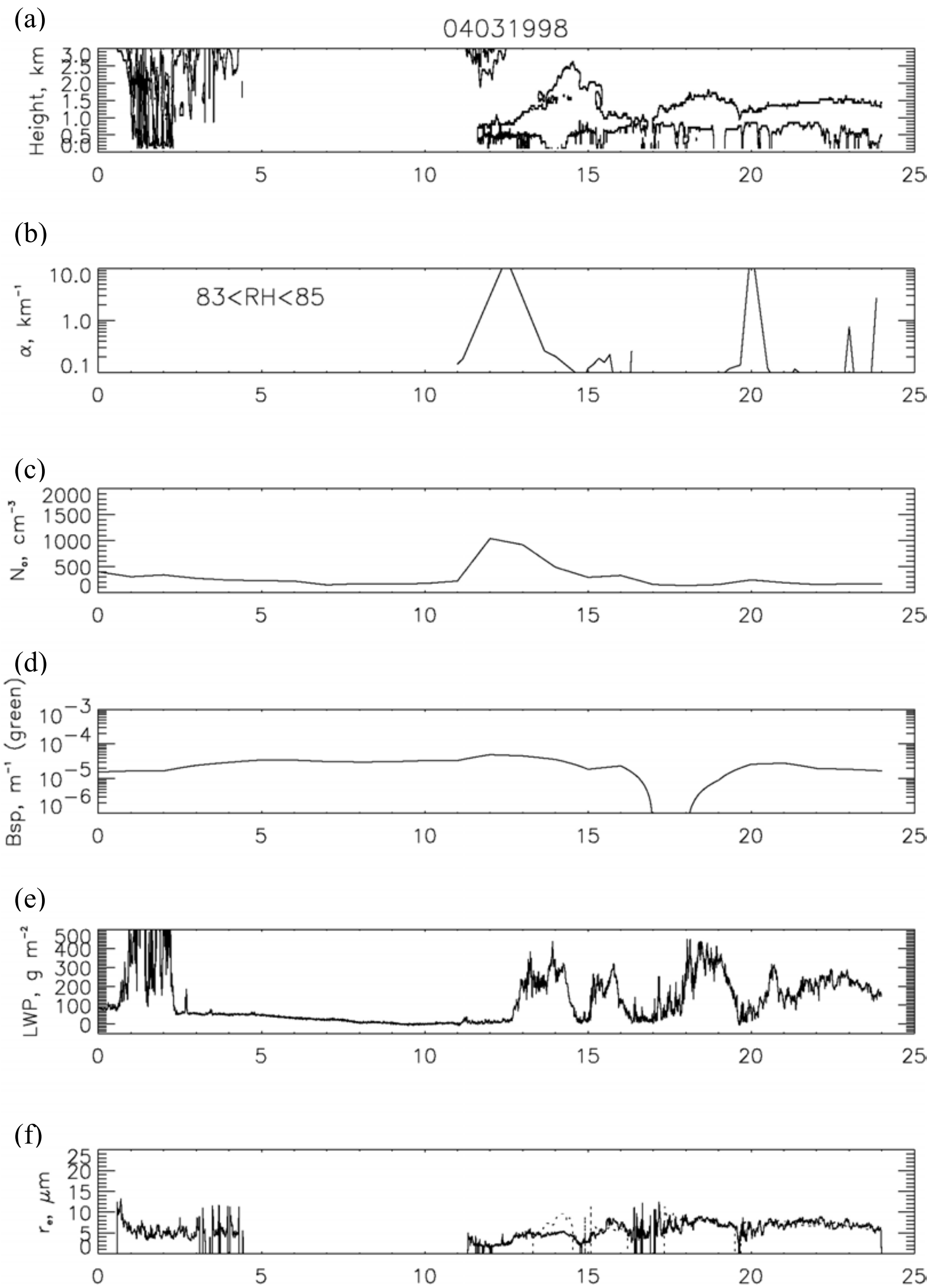

Figure 2. Time series of (a) radar reflectivity (cloud mask), (b) Raman lidar extinction (at RH=83-85%), (c) surface aerosol accumulation mode (courtesy of National Oceanic and Atmospheric Administration/ Climate Monitoring and Diagnostics Laboratory), (d) surface-scattering coefficient, (e) cloud LWP, and (f) r_e derived by the modified radar/radiometer method (solid line) and the Min and Harrison (1996) method (dashed line, daytime only). The profile derived from the radar/radiometer method is averaged to produce a single value for comparison.

Modeling

Numerical modeling is being used to address the indirect effect in a number of different ways. An underlying goal of this research is to improve our understanding of the connection between aerosol and cloud microphysics. To this end, we are using models to augment our understanding of the link between various parts of the system and to interpolate information where necessary.

Simulation of aerosol uptake of water vapor and growth into cloud droplets. Lagrangian parcel models are being used to simulate the uptake of water vapor by particles, and their growth to cloud droplet sizes (Feingold et al. 2001). The model traces an updraft in the Lagrangian sense for given initial conditions of temperature, pressure and relative humidity, and aerosol size distribution and composition. It calculates the changes in temperature, pressure, and supersaturation as well as the uptake of water vapor by the aerosol particles, and subsequent condensation growth in the cloud. The input to the model is a size distribution of aerosol particles (with assumed particle chemistry), a vertical wind profile (ideally we would need a Doppler lidar to provide this, but the cloud radar will suffice), and surface temperature and pressure. The model can be run either as an adiabatic parcel or as an entraining parcel. The model is being used to make the link between vertical air motions (and associated supersaturation production) and cloud microphysics (observed vs. calculated r_e) within the context of either the surface aerosol distributions (for well-mixed boundary layers) or the subcloud extinction measurement and ambient thermodynamics. The model will be used to test for self-consistency between observed parameters and to explore the sensitivity of drop activation to various parameters such as aerosol size distribution and chemical composition.

Simulation of the indirect effect using a large-eddy simulation (LES) model. For the purposes of exploring the interaction between dynamics, aerosol-cloud microphysics, radiation, and chemistry, we will use a sophisticated LES model (Feingold et al. 1994; Feingold and Kreidenweis 2002). The model includes a size-resolved representation of aerosol and drop size distribution and simulates the activation and growth of drops in a turbulent boundary layer. It has recently been upgraded to include representation of aqueous production of sulfate and subsequent feedbacks to aerosol-cloud interactions. It is a much more realistic representation of boundary-layer dynamics and the coupled microphysical/dynamical system than the parcel model. It also addresses the problem of aerosol-cloud interaction on the relevant spatial/temporal scales (order of 100 m and a few seconds). Once knowledge of these processes is advanced on these small scales, this information can be used to improve representation of the indirect effect in regional models and general climate models. Sample output from the LES for a system simulating aerosol-cloud chemistry interactions is shown in Figure 3.

Summary

By using ground-based, in situ measurements, ground-based remote sensors, as well as numerical models, we will produce valuable data for evaluation of the indirect effect that will benefit the satellite and general climate model communities, and therefore, our climate forecasting capabilities.

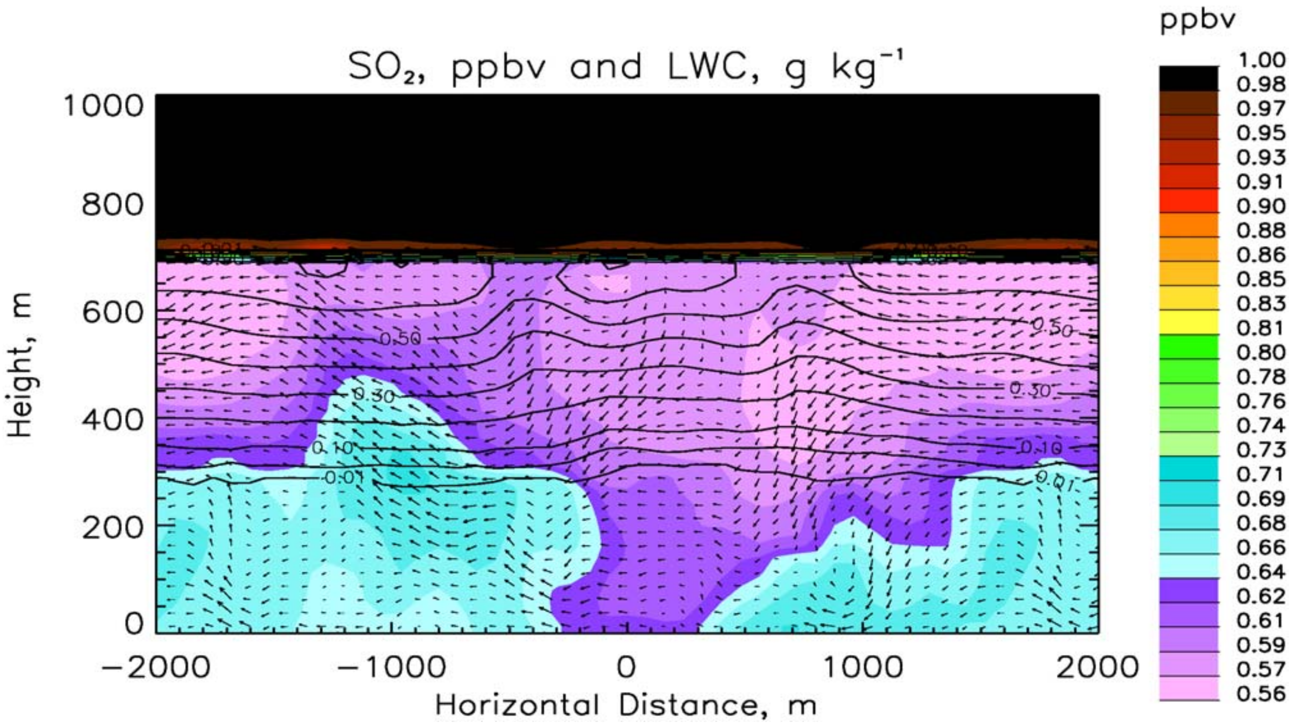

Figure 3. Sample output from the LES for a stratocumulus-capped boundary layer. Solid contours represent cloud liquid water, color-flooded contours represent gas-phase SO_2. See Feingold and Kreidenweis (2002).

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