Surface-Based Remote Sensing of the Aerosol Indirect Effect at Southern Great Plains

G. Feingold and W. L. Eberhard
National Oceanic and Atmospheric Administration
Environmental Technology Laboratory
Boulder, Colorado

D. E. Vernon and M. Previdi
Rutgers University
New Brunswick, New Jersey

Abstract

We have demonstrated first measurements of the aerosol indirect effect using ground-based remote sensors at the Southern Great Plains (SGP) site. The response of non-precipitating, ice-free clouds to changes in aerosol loading is quantified in terms of a relative change in cloud-drop effective radius (r_e) for a relative change in aerosol extinction under conditions of equivalent cloud liquid water path (LWP). This is done in a single column of air at a temporal resolution of 20 s (spatial resolution of ~100 m). Cloud-drop r_e is derived from a cloud radar and microwave radiometer (MWR). Aerosol extinction is measured below cloud base by a Raman lidar. Results suggest that there is good correlation (0.67) between the cloud response and a measure of cloud turbulence. We have not found clear relationships between the cloud response and the back trajectories.

Introduction

The first aerosol indirect effect (Twomey 1977), suggests that increased concentrations of atmospheric aerosol will result in higher concentrations of cloud condensation nuclei (CCN), increased cloud droplet concentrations, and smaller droplets. Twomey clearly stated that the hypothesis applies to clouds of equal liquid water content (LWC); however, this constraint is difficult to achieve with in situ measurements and is seldom applied in analyses of the first indirect effect. This creates an ambiguity; cloud droplets may be smaller because the cloud has less water, and therefore less potential to grow large drops; or the cloud may indeed have smaller drops because there are more condensation sites for the same amount of water.

Satellite remote sensing plays an important role in monitoring the aerosol indirect effect at global scales. Satellites typically measure the effect of aerosol (represented by optical thickness τ_a or other aerosol indices) in cloud-free regions on the mean drop size or reflectance in adjacent cloudy regions (e.g., Kaufman and Nakajima 1993; Breon et al. 2002). It is unclear to what extent the path-integrated aerosol is representative of the aerosol entering the clouds.

The current work uses ground-based remote sensors to address the indirect effect for clouds of similar LWP. A more complete description can be found in Feingold et al. 2003. It quantifies the change in cloud drop size (retrieved using a cloud radar and MWR) in response to a change in aerosol amount (represented by subcloud Raman lidar extinction α at 355 nm). The high temporal resolution of the measurements (~20 s) enables us to measure the response of the cloud at scales appropriate to cloud droplet activation. The simultaneous measurement of cloud LWP (MWR) allows this response to be placed within the context of macroscopic changes in the cloud.

Measurements

We use the long-term dataset acquired at the SGP Atmospheric Radiation Measurement (ARM) site in Oklahoma, USA - a rural, continental site which experiences a variety of aerosol conditions. The retrieval is applied to convective regions of non-precipitating, ice-free clouds. Precipitation is avoided because it obscures the formative stages of a cloud. During the summer months, contamination of radar reflectivity by insects exacerbates retrieval of cloud microphysics. Therefore, analysis is restricted to the spring and fall, when insect activity is low. The primary instruments are MWR, millimeter wave cloud radar (MMCR), and Raman lidar. A common temporal resolution of 20 s is used. Aerosol parameters are typically recorded at a resolution of minutes, but are interpolated to 20 s resolution because they vary at a much slower rate than cloud parameters. We apply the Frisch et al. (2002) retrieval which uses MMCR to derive profiles of droplet, r_e, under the assumption of a constant drop concentration N_d, and fixed distribution breadth. The latter assumption is frequently met in non-precipitating, warm clouds. Values of r_e are weakly sensitive to the prescribed value of N_d (re $\sim N_d^{-1/6}$) but indirect effects as quantified here are not (see below). The retrieved r_e profile is scaled so that LWP is conserved.

Results

We focus on clouds that are ice-free, single layered, non-precipitating, and free of airborne insects. Seven cases exhibiting a fairly significant change in aerosol over a period of one day are highlighted (Table 1). Figure 1 shows time series of various fields on April 3, 1998. After ~13:00 Universal Time Coordinates (UTC), a single-layered boundary layer cloud covers the site. Intermittent precipitation (avoided in the analysis by considering periods when the column maximum Z is < -17 dBZ and LWP <150 gm-2) is manifested by cloud masks lowering to the surface. During non-precipitating periods, cloud base is at ~700 m. Cloud-top-weighted drop effective radii range from 5µm to 8 µm; Aerosol extinction (at z = 350 m) and surface N_a vary over large ranges. Polluted air arrives at the site at about 11:00 UTC but aerosol parameters decrease thereafter, possibly due to precipitation scavenging. The indirect effect (IE) is quantified as

$$\mathrm{IE} = -\frac{d \ln r_e}{d \ln a} \tag{1}$$

(Feingold et al. 2003) which throughout will represent the relative change in mean cloud r_e for a relative change in α, for clouds having the same LWP. Although r_e is in general dependent on the size distribution and composition of aerosol, α (or τ_a) is a widely used proxy. Equation 1 places less reliance on the

Table 1. Summary of average IE, information on 5-day back trajectory, and mean value of column-maximum standard deviation of boundary layer vertical velocity σ_w.

Date (mm/dd/yy)	Trajectory	σ_w, ms^{-1}	IE
04/15/98	W (Pacific)	1.4	0.16
04/14/01	Gulf of Mexico	1.2	0.15
04/04/98	N (Canada)	0.8	0.11
03/30/00	N	1.1	0.11
12/21/00	N + Gulf of Mexico	0.6	0.08
0403/98	NW + local TX, OK, KS	1.1	0.07
10/04/99	NW	0.8	0.02

absolute measures of parameters such as α and r_e, which is of obvious advantage when using remote sensors. This explains the insensitivity of IE to the choice of fixed N_d in the re retrievals. Mean values of IE are given in Table 1. Figure 2 shows r_e as a function of α on April 3, 1998. Analysis considers updrafts >0.1 ms^{-1} only, in order to focus on activation events and to reduce biases due to advection of droplets into the sample volume. Data are sorted into three narrow LWP bands defined such that there is a 10% increase in LWP from one to the next. A random variation of +/- 15 gm^{-2} is added to LWP to reflect uncertainties in this measurement. Over the range 80 gm^{-2} < LWP < 150 gm^{-2}, IE ranges from about 0.04 to 0.09 with a mean of about 0.07 (Table 1).

Discussion and Summary

Ground-based remote sensing may be a powerful tool for detection and quantification of the first indirect effect—defined here in the form originally suggested by Twomey (1977). The retrieved values of IE in this work range from 0.02 (October 4, 1999) to 0.16 (April 15, 1998). In comparison, Nakajima et al. (2001) derived an equivalent value of IE = 0.17 over the oceans. Breon et al. (2002) used the POLarization and Directionality of the Earth Reflectances (POLDER) to quantify the indirect effect on a global scale and found IE ~0.04 - 0.085, i.e., much weaker than that suggested by Twomey and some of our analyzed events, but similar to Figure 2. However, because primary controlling factors such as LWP and aerosol size/composition were not measured, it is not clear whether their small IE values are truly representative of the cloud response to aerosol.

Analysis of seven cases gives a range of responses of cloud drop size to aerosol that are well correlated with a measure of cloud turbulence (r = 0.67; Table 1 or Figure 3) (e.g., Leaitch et al. 1996) and somewhat related to air trajectories; trajectories of maritime origin and those from the north tend to have stronger responses, while those from the northwest and that also have significant local residence have weaker responses. Further work is needed to relate these trajectories to aerosol size and composition.

The main advantage of the method is that the effect of aerosol on cloud can be examined in a single column of air at the scale of cloud droplet formation, and at high temporal resolution. The ranging capabilities of a lidar, and the fact that it is located beneath the cloud, provide a measure of a property of the aerosol that is entering the cloud. The ranging capabilities of radar provide a profile of r_e. The measurements can be placed within the context of macroscale changes in fundamental cloud properties such as LWP. It is suggested that a coordinated approach to measuring the indirect effect that uses the complementary strengths of satellite-based remote sensing, surface-based remote sensing (at fixed ground sites or on roving ships), and in situ aerosol measurements will produce valuable data for evaluation of the indirect effect, that will greatly benefit our climate forecasting capabilities.

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Corresponding Author

Graham Feingold, Graham.Feingold@noaa.gov, (303) 497-3098

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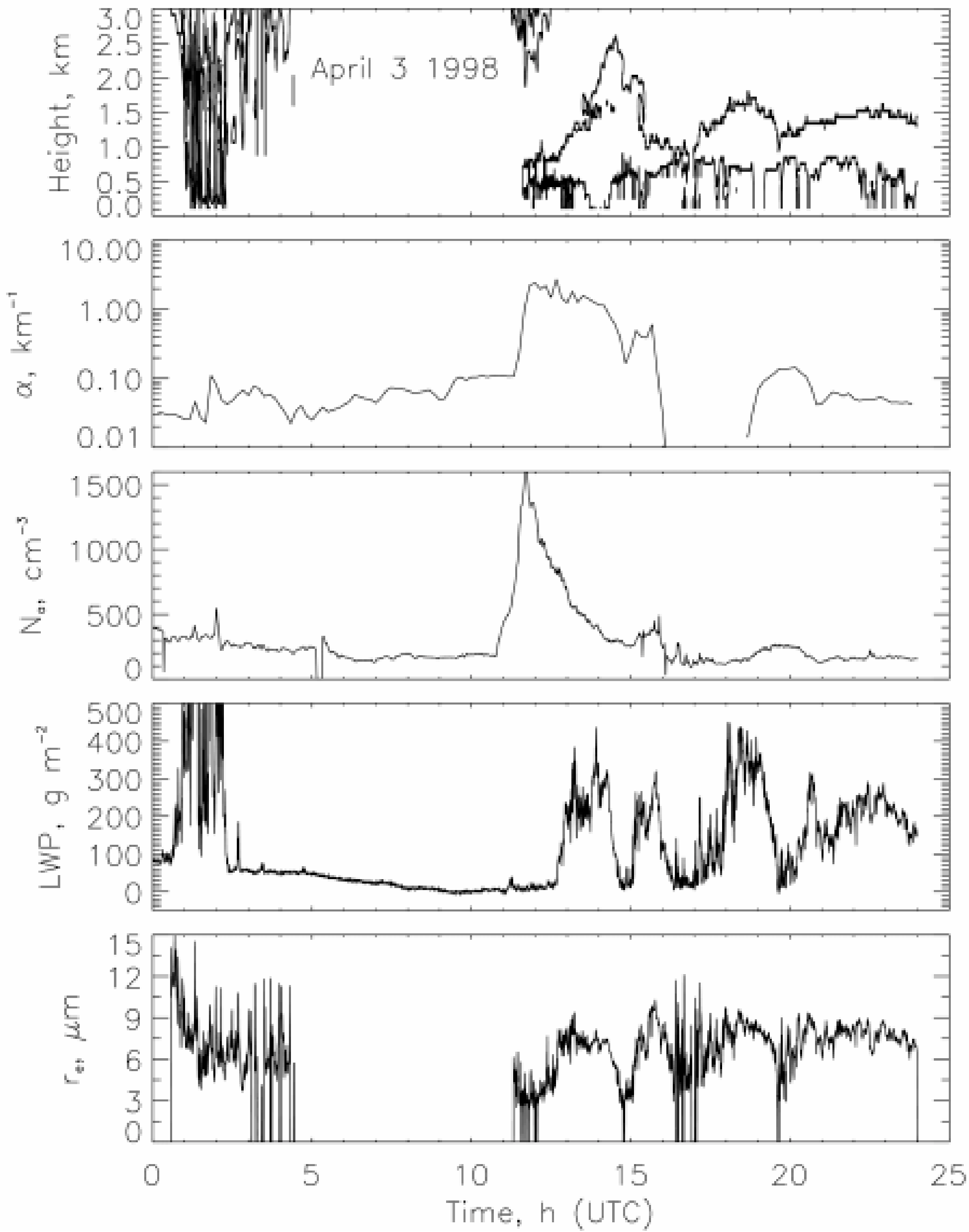

Figure 1. Time series of radar-derived cloud masks, aerosol extinction α, surface aerosol accumulation mode number concentration N_a, LWP, and cloud-top weighted mean r_e on April 3, 1998.

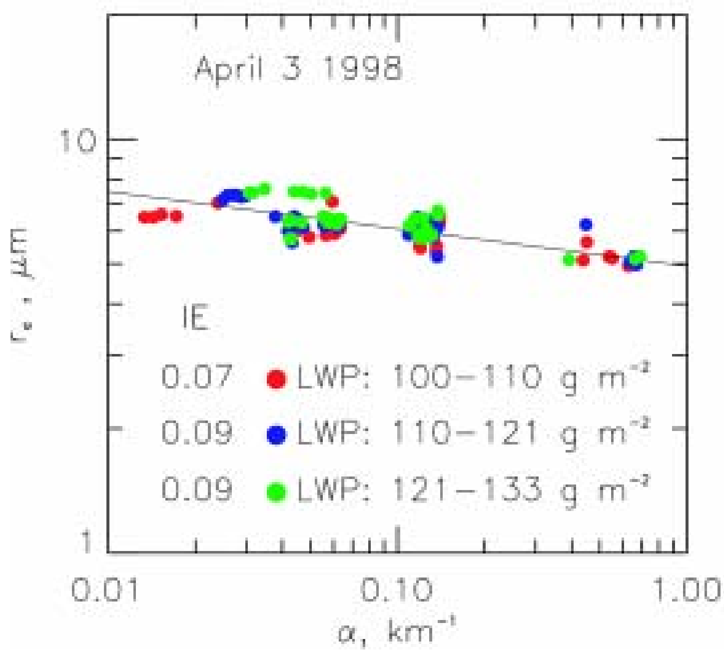

Figure 2. Scatter plots showing mean r_e vs. α for various LWP bands on April 3, 1998. IE is the indirect effect as defined by Equation 1.

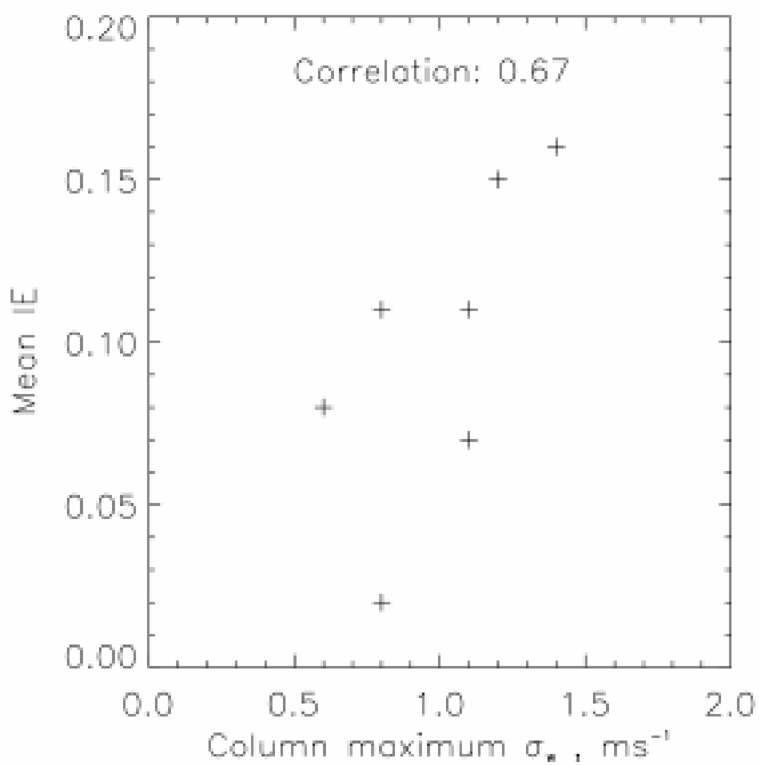

Figure 3. Mean IE vs. column-maximum standard deviation of boundary layer vertical velocity σ_w for each of the seven cases.