First measurements of the Twomey indirect effect using ground-based remote sensors

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[1] We demonstrate first measurements of the aerosol indirect effect using ground-based remote sensors at a continental US site. The response of nonprecipitating, ice-free clouds to changes in aerosol loading is quantified in terms of a relative change in cloud-drop effective radius for a relative change in aerosol extinction under conditions of equivalent cloud liquid water path. This is done in a single column of air at a temporal resolution of 20 s (spatial resolution of ∼100 m). Cloud-drop effective radius is derived from a cloud radar and microwave radiometer. Aerosol extinction is measured below cloud base by a Raman lidar. Results suggest that aerosols associated with maritime or northerly air trajectories tend to have a stronger effect on clouds than aerosols associated with northwesterly trajectories that also have local influence. There is good correlation (0.67) between the cloud response and a measure of cloud turbulence. *INDEX TERMS:* 0305 Atmospheric Composition and Structure: Aerosols and particles (0345, 4801); 0320 Cloud physics and chemistry; 0394 Instruments and techniques; 1610 Global Change: Atmosphere (0315, 0325). **Citation:** Feingold, G., W. L. Eberhard, D. E. Veron, and M. Previdi, First measurements of the Twomey indirect effect using ground-based remote sensors, *Geophys. Res. Lett.*, *30*(6), 1287, doi:10.1029/2002GL016633, 2003.

1. Introduction

[2] The aerosol indirect effect, attributed to *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. Since then a plethora of observational and modeling efforts has applied the term to the effect of aerosol on the cloud system together with associated feedbacks. The general problem of aerosol-cloud interactions encompasses myriad microphysical, dynamical, and even chemical feedbacks that are closely intertwined. *Albrecht* [1989] suggested that increasing the number of CCN suppresses precipitation and results in more reflective clouds both because droplets are smaller, and because a larger liquid water path (LWP) is maintained. However, *Jiang et al.* [2002] showed that elevated polluted layers entrained into clouds may generate dynamic feedbacks that counter the expected increase in cloud albedo by decreasing LWP. The possibility of both positive and negative feedbacks to LWP or albedo is indicative of the complexity of the system.

[3] In situ, airborne observations have played a central role in aerosol-cloud studies [e.g., *Brenguier et al.*, 2000]. These detailed measurements address the fundamental aspects of aerosol and cloud microphysics that are necessary to advance our understanding of aerosol-cloud interactions. Unfortunately aircraft campaigns are costly, labor-intensive and not suited to long-term monitoring purposes. Satellite remote sensing plays an important role 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; *Han et al.*, 1998; *Bréon et al.*, 2002]. It is unclear to what extent the path-integrated aerosol is representative of the aerosol entering the clouds. In some studies, cloud LWP is not considered, which obscures Twomey's indirect effect [*Schwartz et al.*, 2002]; 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.

[4] The current work uses ground-based remote sensors to address the indirect effect for clouds of similar LWP. It quantifies the change in cloud drop size (retrieved using a cloud radar and microwave radiometer) 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; Table 1) enables us to measure the response of the cloud at scales appropriate to cloud droplet activation. The simultaneous measurement of cloud LWP (microwave radiometer) allows this response to be placed within the context of macroscopic changes in the cloud. We do not attempt to trace feedback mechanisms that might occur in the dynamic aerosol-cloud system because it is our intent to isolate the aerosol-cloud interaction aspects of the problem.

2. Measurements

[5] We avail ourselves of a long-term data set acquired at the Southern Great Plains (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 nonprecipitating, 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 and derived products are listed in Table 1. A common temporal resolution of 20 s is used. Aerosol parameters are typically recorded at a resolu-

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Table 1. Summary of Primary Instrumentation and Derived Products

Instrument	Derived Product	Comments	Temporal resolution	Reference
Raman Lidar	α	aerosol extinction, km^{-1} at 355 nm, z = 350 m Avoid deliquescence region and drizzle	10 min (interpolated to 20 s)	*Goldsmith et al.* [1998]
Microwave Radiometer	LWP	35 gm^{-2} < LWP < 150 gm^{-2} Accuracy ±30 gm^{-2}	20 s	*Liljegren* [2000]
Radar	Z, r_e profiles, N_d, cloud boundaries, precipitation, Doppler velocities	Non-precipitating, ice-free, boundary layer clouds	10 s (averaged to 20 s)	*Kropfli et al.* [1995]
Optical Particle Counter	N_a	number concentration of accumulation mode (surface)	1 min (interpolated to 20 s)	*Sheridan et al.* [2001]

tion of minutes, but are interpolated to 20 s resolution because they vary at a much slower rate than cloud parameters.

[6] The *Frisch et al.* [2002] retrieval uses a cloud radar to derive profiles of droplet effective radius, r_e, under the assumption of a constant drop concentration N_d, and fixed distribution breadth. The latter assumption is frequently met in nonprecipitating, warm clouds. Values of r_e are weakly sensitive to the prescribed value of N_d ($r_e \propto N_d^{-1/6}$) but indirect effects as quantified here are not (see below). The retrieved r_e profile is scaled so that LWP is conserved.

3. Results

[7] We focus on clouds that are ice-free, single layered, nonprecipitating, and free of airborne insects. Seven cases exhibiting a fairly significant change in aerosol over a period of one day are highlighted (Table 2).

[8] Figure 1 shows time series of various fields on April 3, 1998. After ~13:00 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 nonprecipitating periods, cloud base is at ~700 m. Drop effective radii (weighted toward cloud top) range from 5–8 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.

[9] The indirect effect IE is quantified as

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

[*Feingold et al.*, 2001] 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 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 r_e retrievals. Mean values of IE are given in Table 2.

[10] Figure 2 shows r_e as a function of α on April 3, 1998. Analysis considers updrafts >0.1 ms^{-1} only. This focuses on activation events and is expected 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. In addition, a random variation of ±15 gm^{-2} is added to LWP to reflect uncertainties in this measurement (Table 1). 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 2). We have avoided LWP > 150 gm^{-2} because the probability of the Z = −17 dBZ threshold being exceeded is high, and because the number of data points for the regression diminishes rapidly.

[11] A similar plot on October 21, 2000 (Figure 3) when five-day back trajectories suggest a northerly source with some recent Gulf of Mexico influence, indicates a similar response ($\overline{\mathrm{IE}} \sim 0.08$), although the conditions are much more polluted as reflected in high α and surface N_a (0.1–0.1 km^{-1} and 1500–3000 cm^{-3}, respectively). The assumption of a constant N_d = 300 cm^{-3} probably overestimates r_e but has no effect on IE values.

4. Discussion

4.1. Connection to Theory

[12] For a homogeneous cloud with drop number concentration N_d, and constant cloud liquid water content LWC

$$\tau_d \propto N_d^{1/3}, \tag{2}$$

[*Twomey*, 1977] where τ_d is the cloud optical depth. Assuming that N_d obeys

$$N_d \propto N_a^{a_1}, \tag{3}$$

one can show that

$$r_e \propto \tau_a^{-a_1/3} \tag{4}$$

and

$$\mathrm{IE} = -\frac{d\ln r_e}{d\ln \tau_a} = -\frac{d\ln r_e}{d\ln \alpha} = \frac{1}{(1-\rho)}\frac{d\ln \rho}{d\ln \alpha} = \frac{a_1}{3}, \tag{5}$$

where ρ is cloud reflectance [*Feingold et al.*, 2001]. A characteristic value of a_1 is 0.7 [e.g., *Pruppacher and Klett*, 1997], yielding IE = 0.23. Note that since $a_1 \leq 1$, $0 \leq \mathrm{IE} \leq 0.33$.

[13] The retrieved values of IE in this work range from 0.02 (October 4, 1999) to 0.16 (April 15, 1998), values that

Table 2. Summary of Average IE and Information on Five-Day Back Trajectory and Mean Value of Column Maximum Standard Deviation of Boundary Layer Vertical Velocity $\bar{\sigma}_w$

Date (mm/dd/yy)	Trajectory information	$\bar{\sigma}_w$ m s^{-1}	$\overline{\mathrm{IE}}$
04/15/98	W (Pacific)	1.4	0.16
04/14/01	Gulf of MX	1.2	0.15
04/04/98	N (Canada)	0.8	0.11
03/30/00	N	1.1	0.11
10/21/00	N + Gulf of MX	0.6	0.08
04/03/98	NW + local TX, OK, KS	1.1	0.07
10/04/99	NW	0.8	0.02

Most events are solid stratocumulus. Shallow cumulus clouds existed on April 15th. Events are listed in order of decreasing IE. "Local" indicates residence time of a day or two in contiguous states.

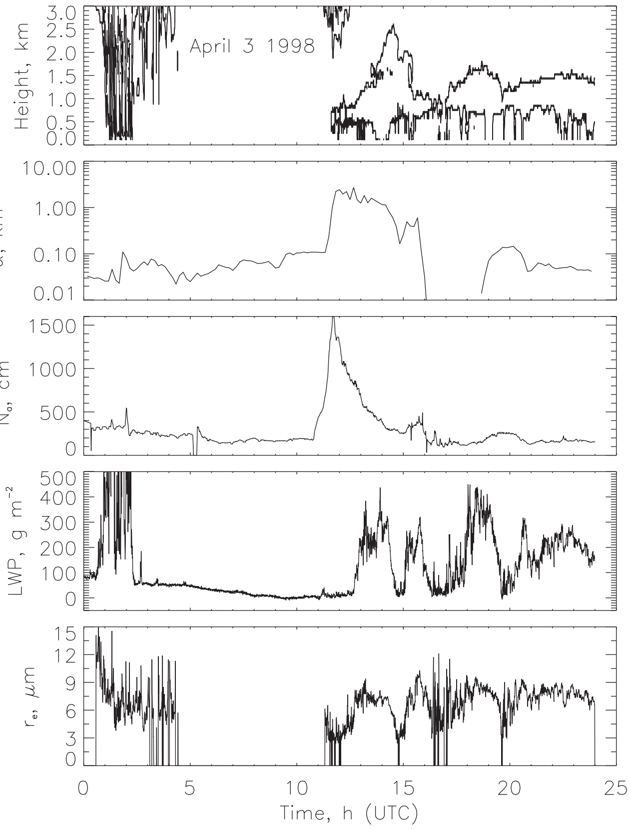

Figure 1. Time series of radar-derived cloud masks, aerosol extinction α, surface aerosol accumulation mode number concentration N_a, LWP, and cloud-top weighted mean r_e on April 3, 1998.

suggest a rather large range of aerosol properties. According to (3), the implication is that $N_d \propto N_a^{0.06}$ on October 4, 1999, and $N_d \propto N_a^{0.48}$ on April 15, 1998. In comparison, *Nakajima et al.* [2001] derived an equivalent value of IE = 0.17 over the oceans, or $N_d \propto N_a^{0.51}$.

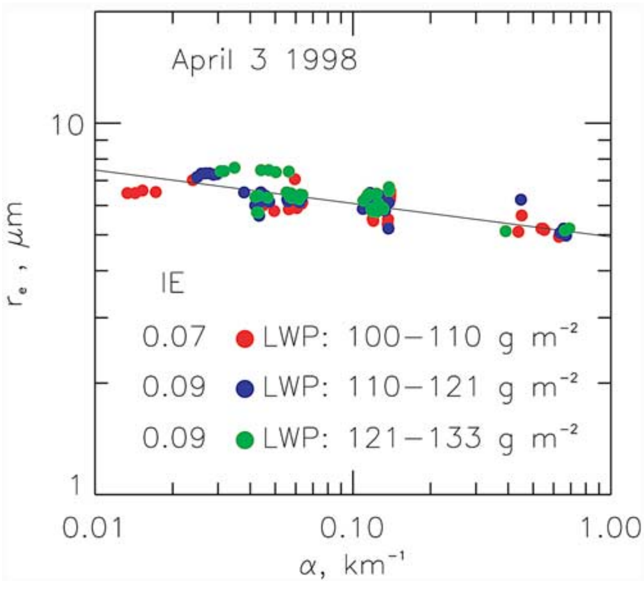

Figure 2. Scatter plots showing mean r_e vs. α for various LWP bands on April 3, 1998. IE is the indirect effect as defined by equation (1).

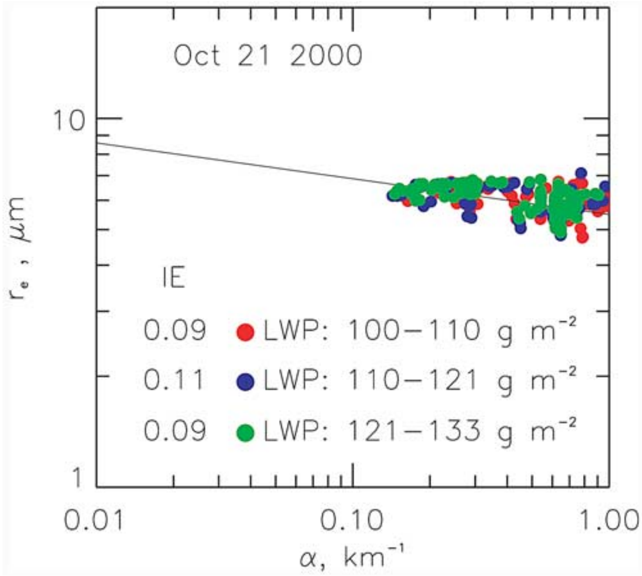

Figure 3. As in Figure 2 but for October 21, 2000.

[14] There are numerous possible reasons for the range of IE. The differences in IE are likely a function of the type of aerosol as reflected in the origin of the air parcel and its trajectory to the site. Table 2 suggests that trajectories with maritime influence, or those from the north have higher IE than those from the northwest that also have a significant local residence time. Cloud turbulence seems to play a role in determining N_d and r_e. Figure 4 shows that there is a good correlation (r = 0.67) between IE and the mean column-maximum standard deviation of the vertical velocity [*Leaitch et al.*, 1996]. All cases, except April 15, 1998, are solid stratus or stratocumulus clouds so a range of IE can exist for a given cloud type.

[15] One of the primary advantages of the proposed method is that short-term events, over which aerosol is unlikely to

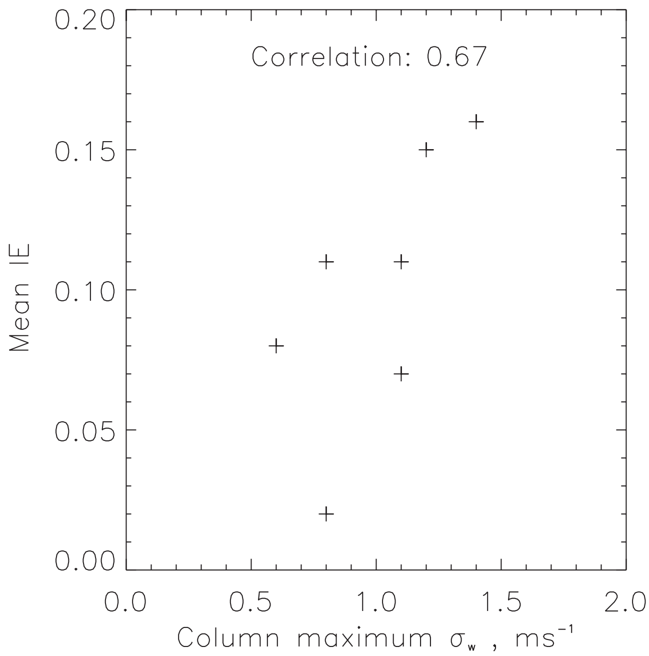

Figure 4. Mean IE vs. column-maximum σ_w for each of the 7 cases.

change its composition, can be analyzed. The rather low temporal resolution (2× per day) satellite data invariably include aerosol of different size distribution, composition, and cloud dynamics, and this may obscure the indirect effect. For example *Bréon 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 Figures 2 and 3. 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.

4.2. Relative Effects of LWP and α

[16] Analysis is extended to highlight the relative importance of LWP and α in determining IE. For simplicity, we ignore the general dependence of IE on aerosol size distribution. From equations (2)–(4), and using

$$r_e = 1.5\frac{\mathrm{LWP}}{\tau_d} \tag{6}$$

[*Stephens*, 1978], where τ_d is the cloud optical thickness, it can be shown that

$$r_e \propto \mathrm{LWP}^{0.33}\alpha^{-a_1/3}, \tag{7}$$

which, at constant LWP, is equivalent to (5). Note that because $a_1 < 1$, r_e is more strongly dependent on LWP than on α, and the effects are of opposite sign. Accurate measurement of LWP is therefore a fundamental problem in quantifying the indirect effect. (Current accuracy is ~±30 gm^{-2}.) This is particularly true at small a_1, i.e., aerosol exhibiting low hygroscopicity. The general form of (7) is corroborated by a power-law regression to α and LWP data from April 3, 1998 which yields $r_e \propto \mathrm{LWP}^{0.34}\ \alpha^{-0.07}$.

5. Summary

[17] The paper shows that 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]. 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) 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.

[18] 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 a radar provide a profile of r_e. The measurements can be placed within the context of macroscale changes in fundamental cloud properties such as liquid water path. However, success depends on the availability of events that have a good range of aerosol amount with little change in aerosol properties. If numerous events are included to achieve this range, successful quantification depends on an ability to stratify data by aerosol size distribution and composition.

[19] 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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