SATELLITE DATA NEEDED TO CONSTRAIN DIRECT AND INDIRECT EFFECTS

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ERFari Factors

$$\Delta(S - S_{clean}) = \frac{dS}{d\tau_a}\frac{d\tau_a}{dB}\frac{dB}{dE}\Delta E$$

Schulz et al. (2006)

$$\Delta\tau_a$$

Δ=anthropogenic change

S=net downward solar flux at TOA

S_{clean}=S ignoring all aerosol

τ_a=aerosol optical depth (extinction or absorption)

B=column mass burden of aerosol

E=emission rate of aerosol or precursor gases

$\frac{dS}{d\tau_a}$ Depends on surface albedo, aerosol single scatter albedo, distribution of clouds and aerosol

ERFaci sums and factors (warm clouds)

$$\Delta R = R\frac{d\ln R}{d\ln N_d}\frac{d\ln N_d}{d\ln CCN}\frac{d\ln CCN}{d\ln E}\Delta\ln E$$

Ghan et al., PNAS, submitted

$$= R\left(\frac{d\ln C}{d\ln N_d}+\frac{d\ln R_c}{d\ln\tau_c}\frac{d\ln\tau_c}{d\ln N_d}\right)\frac{d\ln N_d}{d\ln CCN}\frac{d\ln CCN}{d\ln E}\Delta\ln E \qquad R=CR_c$$

$$\simeq R\left[\frac{d\ln C}{d\ln N_d}+\frac{d\ln R_c}{d\ln\tau_c}\left(\frac{d\ln L}{d\ln N_d}-\frac{d\ln r_e}{d\ln N_d}\right)\right]\frac{d\ln N_d}{d\ln CCN}\frac{d\ln CCN}{d\ln E}\Delta\ln E \qquad \tau_c \propto \frac{L}{r_e}$$

R: "clean-sky" shortwave cloud forcing S_{clean}-$S_{clean,clear}$ (Ghan, 2013)

ΔR: ERFaci R_c: in-cloud R C: liquid cloud fraction

τ_c: cloud optical depth N_d: cloud droplet number

CCN: CCN at cloud base (0.3% supersaturation)

E: anthropogenic emission

L: liquid water path r_e: droplet effective radius

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lifetime effect

albedo effect

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Ice clouds

- Cloud top temperature
- Ice water path
- Cloud phase
- Crystal number concentration
- Ice nuclei (dust?) number concentration