Direct Aerosol Forcing: Calculation from Observables and Sensitivities to Inputs

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Abstract

Aerosol radiative forcing, the difference in net radiative flux with and without aerosol, and anthropogenic aerosol radiative forcing, the difference in net radiative flux with and without anthropogenic aerosol, are essential to understanding earth's radiation budget and changes in this budget over the industrial period. These forcings are highly variable in space and time; locally and instantaneously they can be tens of watts per square meter. Characterization of aerosol direct forcing (the forcing in cloud-free sky) at a given time and location such as at Atmospheric Radiation

Measurement (ARM) Climate Research Facility locations, generally relies on measured aerosol extensive and intensive properties and their dependence on wavelength. Extensive properties, which scale linearly with aerosol amount, include measurements of spectral optical depth or the integrated extinction in the total column. Aerosol forcing is commonly characterized as a "forcing per optical depth." Intensive properties, not directly dependent on aerosol amount, are manifested in such measured aerosol properties including single scatter albedo, backscatter fraction and Ångström exponent, often used to characterize the wavelength dependence of optical depth. Situational variables such as solar zenith angle and surface reflectance (the latter also wavelength dependent) also effect the radiaitve forcing. We examine the sensitivity of calculated aerosol radiative forcing and forcing per optical depth to extensive and intensive aerosol properties based on the uncertainties with which these are measurable.

Introduction

A recently established goal by the Intergovernmental Panel on Climate Change is to possess the ability to determine aerosol radiative forcing to within 0.5 W m^{-2}, consistent with global mean climate sensitivity for anthropogenic aerosol. To achieve this goal, aerosol properties needed in radiative forcing calculations must be know to some accuracy. It is required that we understand the aerosol properties that have the greatest influence on radiative forcing and properties for which the greatest uncertainty in measurements occur. The outcome directs the community to the area where the most significant improvements are required in measurements.

Radiative transfer models are used to compute the aerosol direct radiative forcing at any level in the atmosphere with the appropriate input values for aerosol properties. Those properties of primary importance to computing the aerosol direct radiative forcing, and most commonly used as model inputs, are the aerosol optical depth, single scattering albedo, asymmetry factor, surface albedo, and Ångstrom exponent. To provide the sensitivity in radiative forcing to these properties a reasonable range in observations, which varies across space and time, and measurements uncertainties must be known. These variables will change for different regions and aerosol types as well as for different measurement approaches (different instruments) for measuring or deriving properties. As a first attempt, a "base case" representative of the mean and range in aerosol properties over the Northern Hemisphere is chosen for determining sensitivity. Figure 1 shows the locations of all measurement sites used in this data compilation. Long-term datasets from the AERONET network, consisting of remotely sensed aerosol properties, and the National Oceanic and Atmospheric Administration (NOAA) Climate Monitoring and Diagnostics Laboratory (CMDL) aerosol monitoring network, consisting of in situ observations, are compiled to provide a range and average value of aerosol properties relevant to radiative transfer modeling. Southern Great Plains (SGP) values are given in comparison to other regions which consist of mostly oceanic and coastal sites.

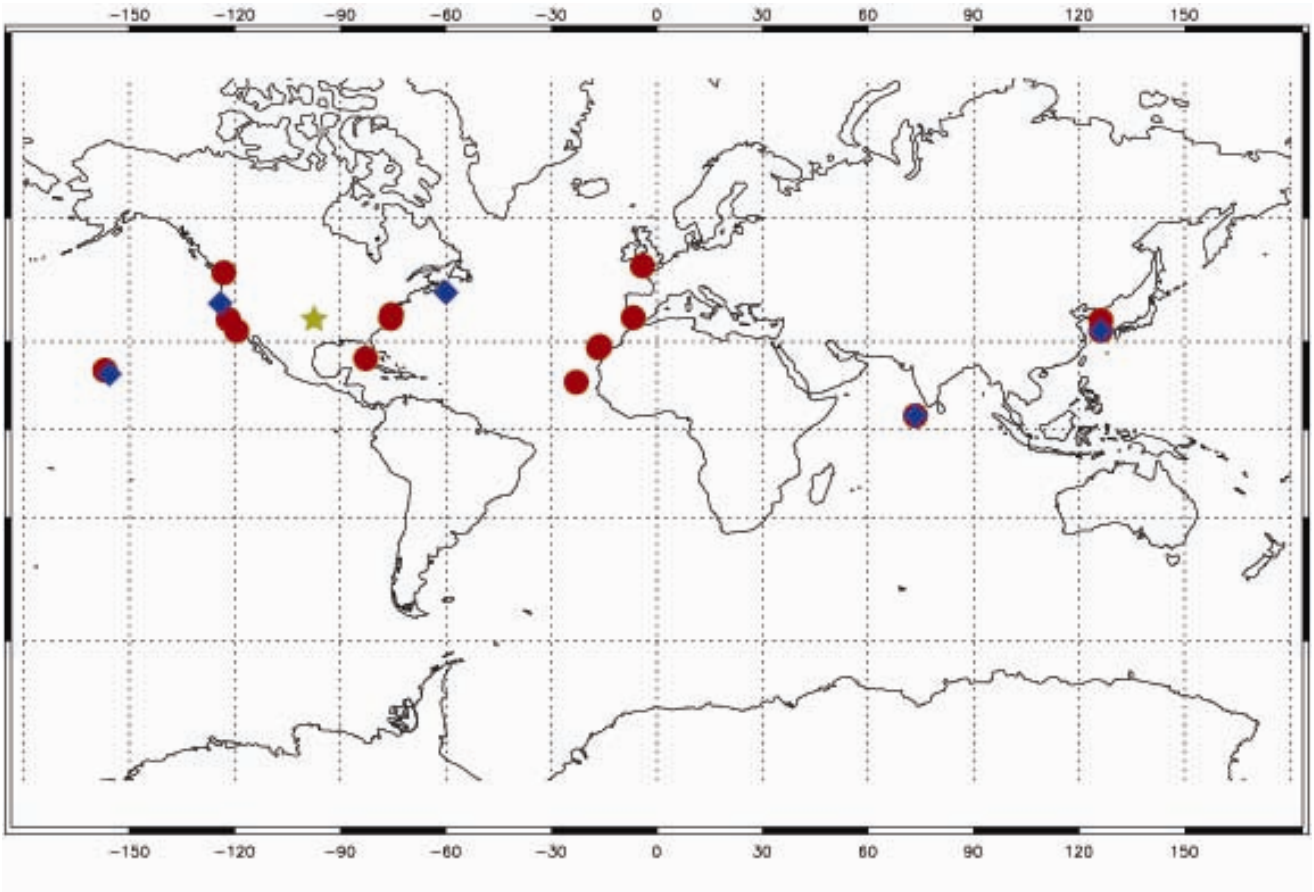

Figure 1. Site locations for aerosol measurements used in this study. AERONET sites are represented by red dots, CMDL sites by blue dots, and the SGP site is indicated by the green star.

Data and Calculations

Comparisons of the observed atmospheric variability to measurement uncertainty by region for each aerosol type of primary importance are presented in Figure 2. For each graph, bars to the left of the vertical dotted line represent the mean (center) and two standard deviations from the mean (top and bottom) for regions in the Northern Hemisphere and the SGP site. Blue bars represent properties from the Cimel sunphotometer at AERONET sites and Dubovik retrievals (Dubovik and King 2000) at 441 nm. The red bars represent properties from in situ nephelometer observations from the CMDL network and, for asymmetry parameter, the Henyey-Greenstein relationship to backscatter fraction (Wiscombe and Grams 1976) at 550 nm. The yellow bars represent asymmetry parameter from a new inversion (Fiebig and Ogren 2005) using in situ data, also at 550 nm. Error bars to the right of the vertical dotted line represent reported measurement uncertainties (U_m) as cited in the table above. For all properties, the observed range is larger than the measurement uncertainty, regardless of the measurement approach. The mean values for each property across all the regions is used as the "base case" for calculating sensitivity to aerosol direct radiative forcing (see Table 2).

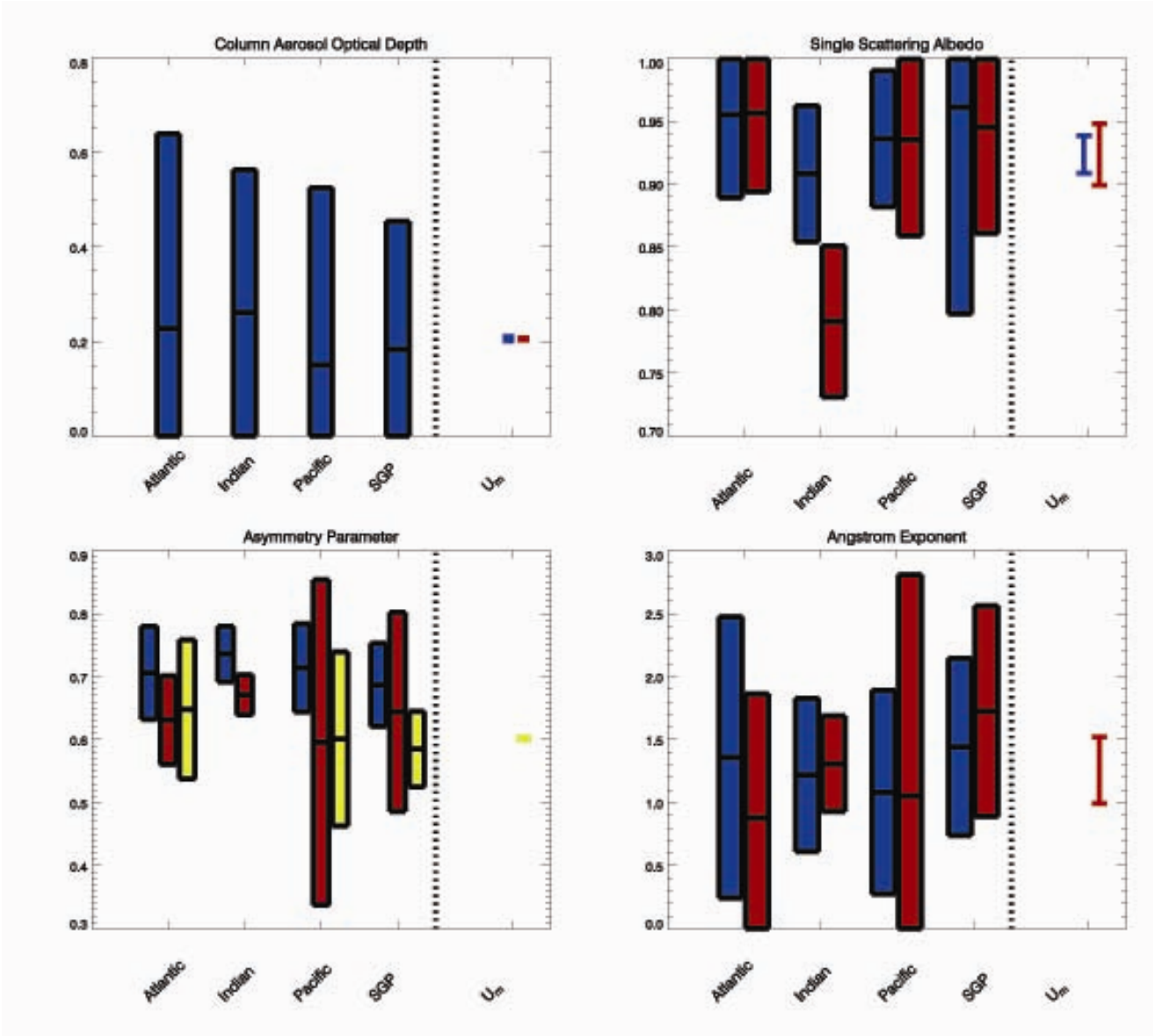

Figure 2. Comparison of atmospheric variability to measurement uncertainty of primary aerosol properties.

Uncertainties in the measurement of each parameter by different instruments must be known to determine where current techniques are sufficient and where further improvement is needed. Table 1 reports some published estimates of measurement uncertainty. While some aerosol properties are directly measured and others are derived from measurements, uncertainty estimates are not reported for all properties.

Table 1. Reported uncertainty in measurement of aerosol properties by various instruments.

Parameter *Instrument*	*Uncertainty**	*Wavelength*	*Source*
Tau			
CIMEL	±0.01	340-1020 nm	Holben et al. 1998
MFRSR	±0.02	415-940 nm	Mitchell and Forgan 2003
ω0			
CIMEL	±0.03	340-1020 nm	Dubovik et al. 2000
Neph+PSAP	<1 μm ±0.014-0.029** 1-10 μm ±0.008-0.023	550 nm	Anderson et al. 1999
	±0.036-0.049***	550 nm	Sheridan et al. 2002
g			
CIMEL			
Fiebig	1%	450, 550, 700 nm	Fiebig and Ogren 2005
å			
CIMEL			
Neph	<1 μm ±0.33-0.45** 1-10 μm ±0.70-0.84	450 nm / 700 nm	Anderson et al. 1999
	±0.49-0.53***	550 nm	Sheridan et al. 2002

*Total size range, all wavelengths unless otherwise noted

**For a range of airmasses

***For a range of scattering coefficients (58-6 Mm^{-1})

The sensitivity of aerosol direct radiative forcing to observed aerosol properties and to measurement uncertainties is demonstrated in Figure 3. The SBDART radiative transfer model (Ricchiazzi et al. 1998) is used to compute fluxes at the top of atmosphere and surface, varying one property at a time while the others are held constant. Sensitivity to the range of observed values is expressed as radiative forcing efficiency (RFE), the direct radiative forcing per unit optical depth (top panes). Sensitivity to measurement uncertainty is expressed as the derivative of RFE with respect to the variation of the aerosol property of interest times its measurement uncertainty (Um). The measurement uncertainty used here is the largest for each property from the table above. The aerosol property of interest and surface albedo are varied over the range in observations shown in the bar graphs while all others are held at the mean value. The means are listed in Table 2. Solar zenith angle is diurnally averaged over the day of the Spring equinox to avoid solar angle effects. Results for the range of latitudes (-90°, 90°) have been computed and those for 35° are presented here.

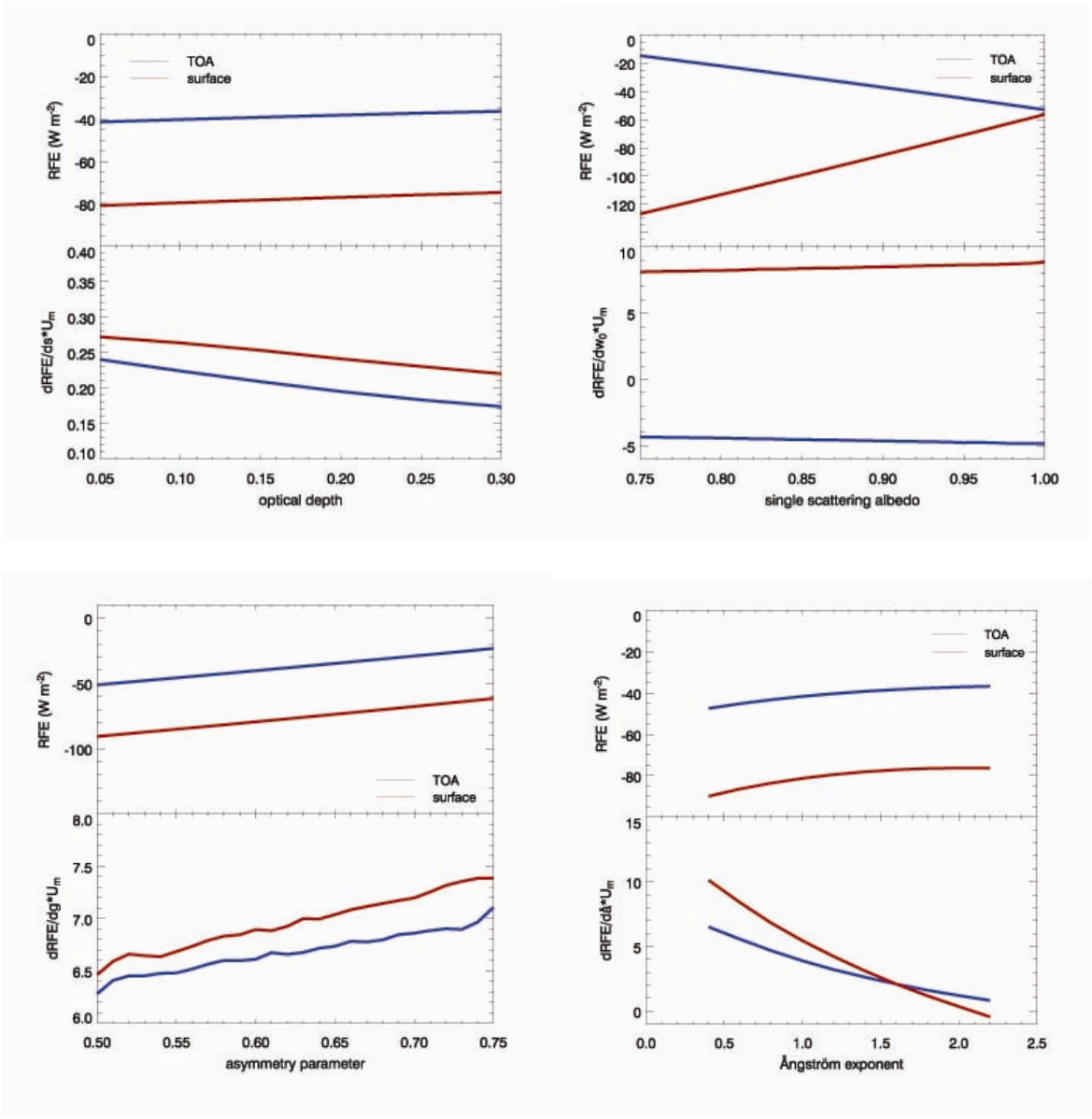

Figure 3. Radiative forcing efficiency (RFE, top panes) and the sensitivity to measurement uncertainty (bottom panes) for the five primary variables relevant to determining aerosol direct radiative forcing.

Table 2. Model constants used in calculating raditave forcing.	
wavelength	0.3-3.0μm
SZA	diurnally averaged over Spring equinox
latitude	35°
standard atmosphere	mid-latitude summer
surface albedo (s) @ 550 nm	0.1
single scatter albedo (ω0) @ 550 nm	0.92
asymmetry parameter (*g*) @ 550 nm	0.6
Ångström exponent (å) @ 550 nm	1.2
number of streams	8

Future Work

An approach to examining the sensitivity of aerosol direct radiative forcing to observed variability and measurement uncertainty has been presented. The current analysis is limited in scope by several factors. Aerosol properties and surface albedo are specified in the model at one wavelength only; the effect of wavelength dependence of the properties on radiative forcing has not been shown. Surface albedo is modeled here as a Lambertian surface which is not representative of natural materials in the earth system. For a more comprehensive discussion of the effects of surface albedo see Ricchiazzi et al. (2005). The properties examined here are those of first order importance to calculating aerosol direct radiative forcing: optical depth, single scattering albedo, asymmetry parameter, Ångström exponent, and surface albedo. These properties in turn depend on others that are regularly measured such as backscatter fraction and *f*(RH), the dependence of scattering on humidity. In the future, the effect of additional or secondary properties on the radiaitve forcing such as relative humidity and the phase function will be examined relative to the primary properties through use of the chain rule.

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