Sensitivity of Clear-Sky Diffuse Radiation to In Situ Aerosol Scattering Parameters

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Introduction

Recent studies of clear-sky radiation indicate that current radiative transfer (RT) models underestimate atmospheric absorption when standard aerosol properties are used. This so-called clear-sky anomaly is manifested in predicted levels of diffuse radiation significantly below those observed at Southern Great Plains (SGP) and other sites in the continental United States (e.g., Halthore et al. 1998 GRL). Other observations at pristine sites do not show a discrepancy (Barnard and Powell 2001, 2001; Kato et al. 1997; Halthore 1998). These results may indicate that the clear-sky anomaly is only observed at sites that are influenced by air parcels that have recently passed near industrialized areas. However, this conclusion is at odds with observations we obtained recently at Palmer Station, Antarctica that also show the anomaly (Payton et al. 2003).

A key question that we consider in this study is whether the variation in the diffuse clear-sky irradiance can be traced to in situ aerosol properties. Our study is based on observations of the ratio diffuse/direct irradiance observed by the multi-filter rotating shadowband radiometer (MFRSR) at the SGP Cloud and Radiation Testbed (CART) site, and modeled with the SBDART radiative transfer code (Ricchiazzi et al. 1998). Vertical profiles of aerosol properties over the SGP CART site have been obtained by aircraft observations over the past few years. This observational program is a joint effort of ARM and the Climate Monitoring and Diagnostics Laboratory (CMDL) the U.S. National Oceanic and Atmospheric Administration (NOAA). The flights are made once or twice a week and include data from a suite of instruments similar to those used in the ground based aerosol observing system (AOS 2003). We used SBDART to compute the diffuse/direct ratio on all days for which the aerosol flight data and estimates of aerosol optical depth from the MFRSR were simultaneously available.

Model Inputs

The total optical depth was derived through an application of Beers law to the MFRSR direct normal irradiance. These results depend on the MFRSR instrument calibrations for MFR head 922 (September 3, 1999, through September 18, 2001) and head 230cc (September 19, 2001, through present) (Michasky 2003). Clear-sky periods were selected by requiring that the retrieved total optical depth remain stable within a 4 hour window near the times of the in situ observations. In addition, total optical depths based on the 30-minute sliding window algorithm were obtained from Michalsky's MFRSR page and used when they were available. Aerosol optical depth (AOD) was computed by subtracting the Rayleigh (at a pressure of 973.5 mb) and ozone (Toms 2003) contributions. The in situ extinction coefficients were regridded to SBDART's numerical grid, which had a vertical resolution of 250 m in the troposphere. These coefficients were used to weight the vertical distribution of optical depth, which extended from the surface to a little less then 4 km altitude. Variation in aerosol properties above 4 km was not considered. The model calculations use the Henyey-Greenstein (1941) form of the scattering phase function. The asymmetry factor used in the model runs were derived from the in situ back-scattering coefficient through a regression relation based on Mie scattering analysis (Figure 1) of aerosol particles with a large range of micro-physical properties. The aerosol single scattering albedo (SSA) used in the model runs was set to in situ absorption coefficient divided by the green channel extinction coefficient (i.e., SSA was assumed to be spectrally uniform).

A final ingredient in the model runs was the surface albedo at the MFRSR wavelengths. This was provided by simultaneous irradiance measurements from the down-looking MFR mounted on a 10 m tower (MFR 10 m). In addition, since the 10 m MFR samples a small part of the region that contributes to the effective surface albedo, readings from the 25 m MFR were used to estimate the uncertainty in the albedo estimates.

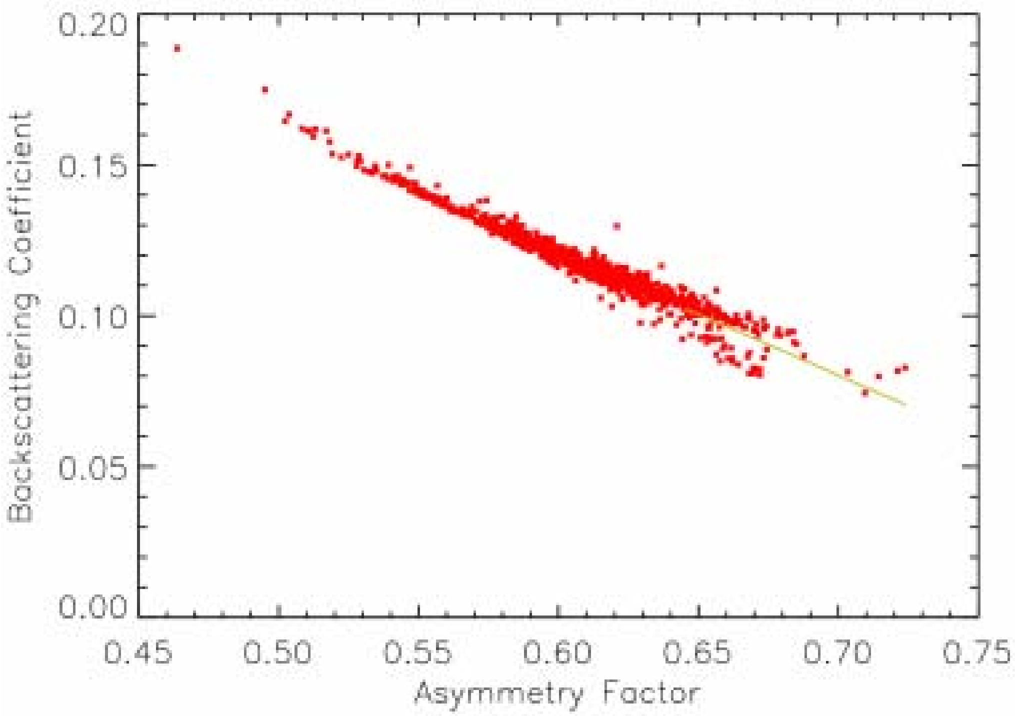

Figure 1. Scatter plot of AOS backscattering coefficient vs. asymmetry factor for a wide range of assumed aerosol microphysical parameters (effective radius, and index of refraction).

Discussion

The ratio of modeled diffuse/direct (Figure 2) is consistently greater than measured values, by up to 20% in some channels. Part of the scatter in this ratio is associated with a switch from MFR head 922 to head 230cc on 2001/09/18. The measurement offset caused by the new head appears most clearly in the

500 nm channel. The population of points closer to the 1/1 line correspond to the newer head. Unfortunately, the observations made with the newer head are now considered unreliable due to light leaks around the spectral filters (John Schmelzer, personal communication). When points after 2001/09/08 are removed, the observations show an even greater deviation from the model runs (Table 1). To relate these deviations to possible causes, we present in Table 2 the perturbations of the model inputs that are required to match the observed diffuse/direct ratio, assuming each input has a linear effect on the diffuse/direct ratio. Surface albedo is not listed in the table because the diffuse/direct ratio is not sufficiently sensitive to surface albedo to allow the discrepancy to be removed by selection of a physically reasonable surface albedo.

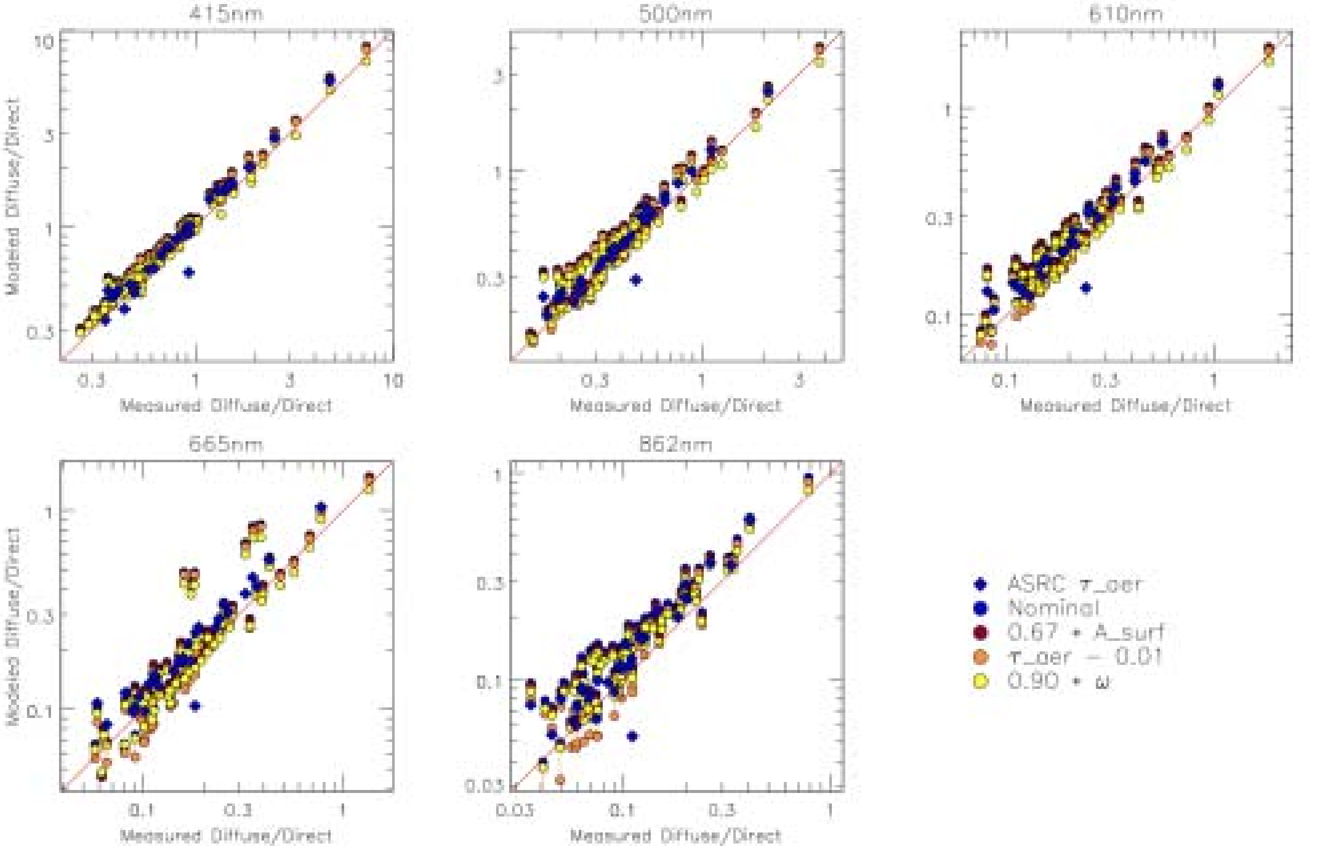

Figure 2. Scatter plot of modeled and observed ratio of the diffuse/direct ratio for each of the first five MFRSR channels. Results for five model calculations are shown. The nominal set of runs used our retrievals of optical depth, the MFR 10 m surface albedo, and the in situ value of SSA (dark blue circles). Sensitivity of the results were evaluated by (1) reducing the surface albedo by 33% – a deviation representative of the difference between the 10 m and 25 m MFRs; (2) decreasing the retrieved optical depth by 0.01; (3) decreasing SSA by 10%; and (4) using Michalsky's 30 minute sliding window optical depths (ASRC τ_aer) when available.

Table 1. Modeled ratio of diffuse/direct divided by observed diffuse/direct. Row Labels: **ALL** – nominal values of AOD, surface albedo and SSA, includes ALL data from September 3, 1999, to December 31, 2002; **Nom** – Same as "ALL" case, but observations limited to those obtained with MFR Head 922 (September 3, 1999, to September 18, 2001); **0.67A** – Same as nominal case, but surface albedo reduced by 33%; **T-0.01** – Same as nominal case, but AOD reduced by 0.01; **0.90ω** – Same as nominal case, but SSA reduced by 10%.

	415 nm	**500 nm**	**610 nm**	**665 nm**	**862 nm**
ALL	1.162	1.174	1.206	1.226	1.411
Nom.	1.245	1.357	1.374	1.470	1.539
0.67A	1.235	1.338	1.349	1.434	1.477
τ-0.01	1.205	1.298	1.282	1.353	1.354
0.90ω	1.136	1.230	1.247	1.327	1.388

Table 2. Required perturbations in model inputs of AOD or SSA that bring modeled results into agreement with observed diffuse/direct ratio. No surface albedo greater than zero can be used to achieve the same effect.

	415 nm	**50 0nm**	**610 nm**	**665 nm**	**862 nm**
AOD	τ -0.063	τ -0.062	τ -0.041	τ -0.040	τ -0.029
SSA	0.77 SSA	0.72 SSA	0.71 SSA	0.67 SSA	0.64 SSA

If the entire diffuse/direct offset is caused by errors in the AOD retrieval, then a reduction in AOD of between 0.02 to 0.06 is sufficient to bring the model into agreement with the observations, with larger AOD reductions required at shorter wavelengths. The optical depths used in the nominal model runs were derived using Beer's law, and therefore rely on the MFRSR radiometric calibration. A straightforward error analysis on the optical depth retrievals indicates that an overestimation of the direct-normal irradiance by an amount dI/I causes an offset in optical depth estimate, $d\tau = -\mu\, dI/I$, where μ is the cosine of the solar zenith angle. The average value of μ in our observational samples was $\langle\mu\rangle = 0.6$. With these considerations in mind, it seems plausible that errors in the radiometric calibration in channels 610 nm, 665 nm and 862 nm may cause offsets in the optical depth estimates large enough to explain the over-estimates of modeled diffuse/direct ratio. However, this explanation does not seem reasonable for the 415 nm and 500 nm channels. For these two channels a radiometric error of about $dI/I = d\tau / \langle\mu\rangle \approx 10\%$ is required, a level of uncertainty much larger than current estimates of MFRSR calibration accuracy.

Similarly, if the entire diffuse/direct offset is caused by errors in the SSA input values, then the SSA estimate must be reduced by 23% at 415 nm and 36% at 862 nm, with a smooth transition in between. Overestimates of this magnitude are much greater than the ~10% uncertainty expected from the AOS instruments. Furthermore, statistical analysis does not support the notion that the diffuse/direct ratio is controlled by the micro-physical properties gathered by the aerosol profile flights. As shown in Figure 3, the normalized diffuse radiation shows no significant correlation to the in situ measurements of SSA ($r^2 < 0.1$). The effect of SSA variations may be obscured by a combination of limited sample size and scatter in other input parameters, particularly the optical depth. However, this lack of correlation and the difficulty of associating the discrepancy with uncertainties in either remote-sensing AOD or in situ SSA measurements suggest several possibilities:

- The in situ absorption properties of atmospheric aerosols are not well characterized by current aerosol monitors.
- Current radiative transfer models may be missing an important gaseous absorber that contributes a continuum absorption profile that primarily affects the shorter wavelength part of the visible spectrum.
- The contribution of AOD from layers above the 4 km aerosol flight ceiling is large and is dominated by highly absorbing aerosols.

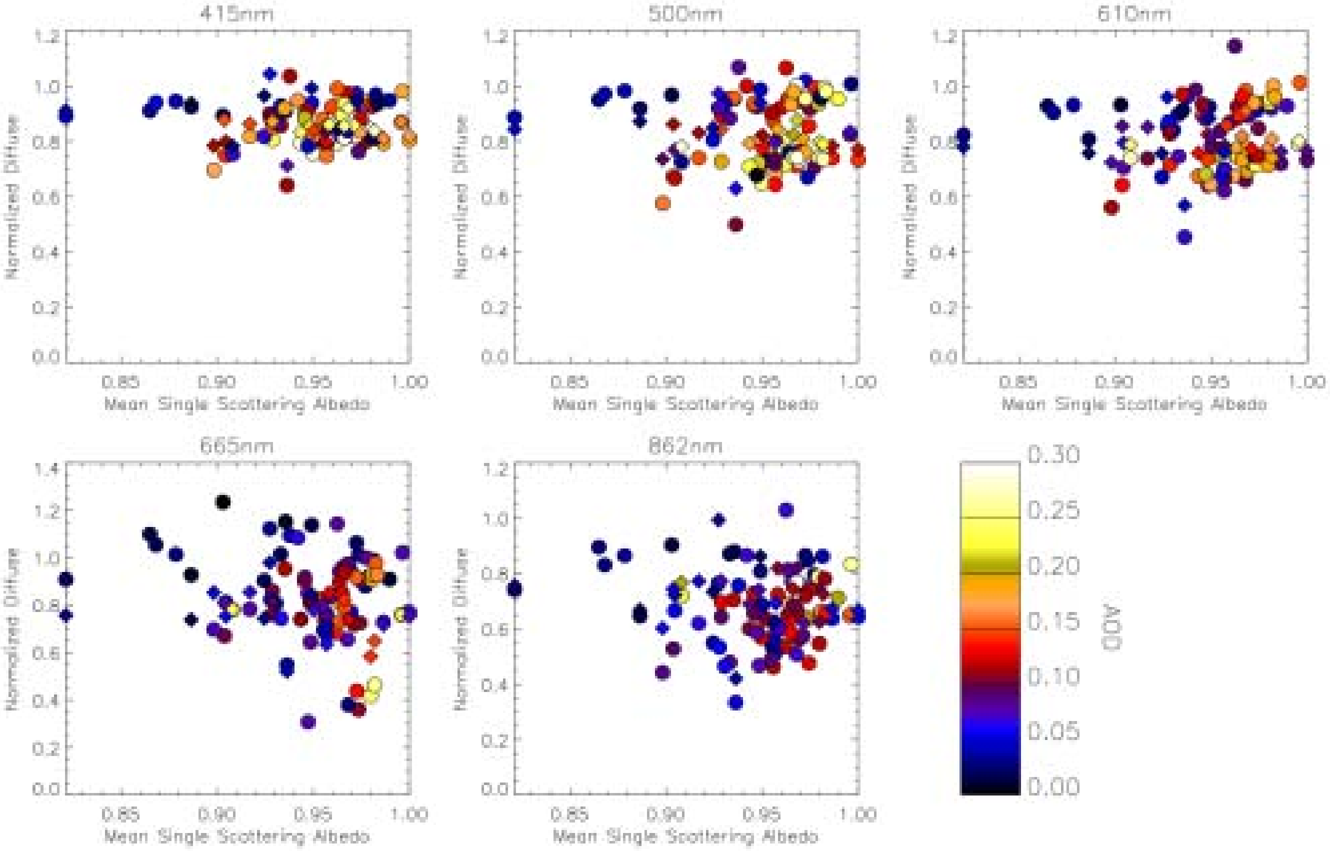

Figure 3. Scatter plot of normalized diffuse irradiance versus effective SSA. The normalized diffuse irradiance is the measured diffuse irradiance divided by the modeled diffuse irradiance for nominal values of aerosol optical depth and surface albedo, but with the SSA = 1.0. The effective SSA is the vertical average of the in situ SSA weighted by the aerosol optical depth at each level.

The first two possibilities have been suggested by other workers, but have not yet lead to any conclusive results. The last possibility could be explored either by extending the vertical extent of the aerosol profile flights or by placing a radiometer on the profiling aircraft to check whether the downwelling radiation at 4 km altitude is consistent with model predictions for a pristine atmosphere. Observations of downwelling irradiance obtained at 7km altitude during the ARESE II experiment show very good agreement with model predictions of downwelling irradiance (within a few percent; O'Hirok, private communication). Air-borne observations of diffuse and direct radiation combined with the aerosol profile data would provide very valuable insights into this problem.

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