

# A Synergetic Study of Solar Fluxes and Aerosol Properties Under Clear-Sky Conditions

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## Introduction

Several recent studies indicate that our ability to model the transfer of solar flux in the clear atmosphere is still fraught with significant uncertainties (Arking 1996; Charlock and Alberta 1996; Kato et al. 1997; Li et al. 1997; Halthore et al. 1997). The treatment of aerosol is often considered as a more likely source for the discrepancy. Presented here is an analysis of the synergy between aerosol optical properties and solar radiative flux measurements made under clear-sky conditions during the Atmospheric Radiation Measurement (ARM) experiment in Oklahoma.

Solar flux data are from two observing systems: the Solar and Infrared Radiation Observing System (SIROS) and Broadband Solar Radiation Network (BSRN) from 1994 to 1997. The variability of observed direct and diffuse flux components and their relation to aerosol properties are discussed and compared with modeling results. In situ measurements of aerosol properties from the ARM Aerosol Observing System (AOS) are analyzed. The MODTRAN 3.5 radiative transfer model combined with the adding-doubling algorithm was used for computation of shortwave broadband fluxes and compared to LOWTRAN-7 results.

## Comparison Between Measured and Modeled Fluxes

We compared the model results to observations of several ARM intensive observation periods (IOPs): April 1994, the ARM Enhanced Shortwave Experiment (ARESE) conducted during autumn 1995, and the spring-summer 1996 IOP. As input for the first two IOPs, we used the datasets prepared under the CERES (Cloud and Earth Radiant Energy System)/ARM/GEWEX (Global Energy and Water Experiment) project (CAGEX) (Charlock and Alberta 1996). In the ARESE dataset, diffuse fluxes were substituted by BSRN 30-minute averages, unlike the SIROS values used by CAGEX. For the 1996 IOP we created a dataset for model verification primarily from observations stored in the ARM central archive, and aerosol optical

thickness (AOT) retrieved by J. J. Michalsky on the basis of the multifilter rotating shadowband radiometer (MFRSR). For the 1996 IOP we selected data that met the following conditions:

1. There was no apparent presence of cloud indicated by direct and diffuse components during  $\pm 30$ -minute intervals around the launch of radiosonde.
2. AOT was derived from MFRSR measurements at that time.
3. There were simultaneous measurements of atmospheric vertical profiles from balloon-borne sounding system (BBSS), single-scattering albedo (SSA), and particle number concentrations (PNC) from AOS.

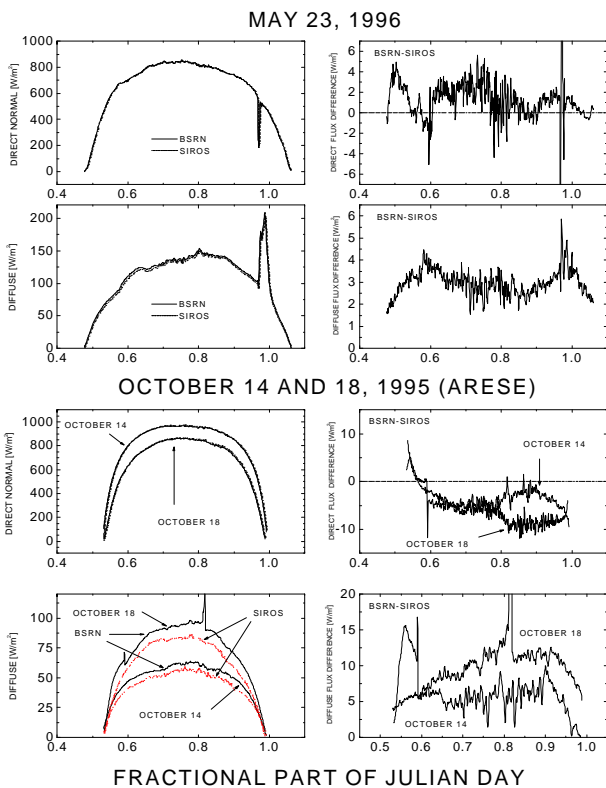
LOWTRAN-7 and MODTRAN 3.5 (Kneizys et al. 1988) were employed to compute atmospheric transmittance. It served as input for the adding-doubling algorithm to account for the scattering processes. We applied the continental model of aerosol according to WCP-112 (1986). A spectral course of aerosol extinction was fitted by the Lundholm-Angstrom formula [ $\tau(\lambda) = \tau_0 (\lambda_0/\lambda)^{\alpha}$ ] to match observed and model aerosol properties. The total AOT was scaled to observed values. Spectral and angular-dependent surface albedo for grassland according to Rutan and Charlock (1997) were assumed in model calculations. The mean differences between model derived quantities and observations are given in Table 1.

For April 1994, the agreement between model results and observations is good: the differences being  $6.8 \text{ W/m}^2$  and  $-0.9 \text{ W/m}^2$  for direct and diffuse components, respectively. For the ARESE, the agreements deteriorate, but are better than for those obtained in the CAGEX 2.1. For example, our analysis showed a difference of  $8.1 \text{ W/m}^2$  for diffuse flux, relative to  $21.1 \text{ W/m}^2$  for CAGEX 2.1. Overall, the results shown in Figure 1 demonstrate the existence of a significant bias for diffuse flux measurements during the ARESE. The disagreement between model and observation for 1996 IOP is similar to that found for ARESE.

**Table 1.** The mean differences between modeled and observed fluxes.

Period	N	Direct Horizontal				Diffuse				
		Mod W/m <sup>2</sup>	Obs <sup>(a)</sup> W/m <sup>2</sup>	$\Delta$ W/m <sup>2</sup>	%	Mod W/m <sup>2</sup>	Obs <sup>(a)</sup> W/m <sup>2</sup>	$\Delta$ W/m <sup>2</sup>	%	
April 1994	L7	55	658.7	651.9	6.8	1.1	113.1	114.0	-0.9	0.2
LOWTRAN 7			479.2		14.0	3.6	76.9		8.5	16.1
ARESE, autumn 1995	132		---	465.2	---	---	---	68.4	---	---
MODTRAN 3.5			476.2		11.0	2.8	76.5		8.1	15.3
Spring-summer 1996	M3.5	37	596.6	580.3	16.3	2.8	107.6	94.7	12.9	15.6

(a) BSRN observations were used for comparison.



**Figure 1.** BSRN and SIROS fluxes for ARESE and spring 1996 IOPs.

Two studies reported very good agreement between model estimated and measured direct flux for April 1996 (Halothore et al. 1997) and for summer 1996 (Fu et al. 1998). The average difference for direct normal component was found to be less than 5 W/m<sup>2</sup> with standard deviation around 10 W/m<sup>2</sup>. Our difference for direct horizontal flux is 16.3 W/m<sup>2</sup>, which corresponds to 22.1 W/m<sup>2</sup> for direct normal flux.

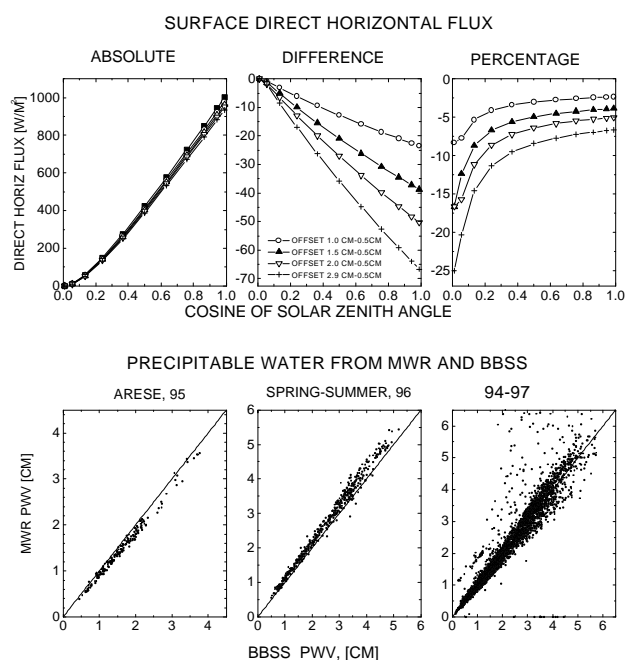
There are two possible explanations for the difference. Observations used by Halothore et al. (1997) were based mainly on active cavity radiometer (ACR) data. We used

data from BSRN. The average difference (ACR-BSRN) was 7.7 W/m<sup>2</sup> and the difference (ACR-SIROS) was 9.9 W/m<sup>2</sup> for the data used by Halothore et al. For April 1996, the average difference between our calculations and BSRN observed values was 13.1 W/m<sup>2</sup> for direct normal component. Were the ACR data used in our study, the difference would be narrowed to less than 5 W/m<sup>2</sup>. The remaining difference can be attributed to a small variation in AOT due to different sources of aerosol properties (Cimel sun photometer observations versus MFRSR) and precipitable water vapor (PWV) amount due to different vertical resolution and PWV measurements.

The uncertainties associated with PWV may serve as a partial explanation of the discrepancy between our results and results reported in Fu et al. (1998). Using identical input atmosphere vertical profiles for CAGEX 1 and 2, we obtained almost the same results for direct component. The difference was less than 3 W/m<sup>2</sup>. For summer 1996, we used BBSS vertical profiles of water vapor; whereas, Fu et al. scaled these profiles to PWV retrieved from microwave radiometer (MWR) observations. Figure 2 shows a comparison between these two datasets and the results of a sensitivity test of direct flux to PWV amount.

The MWR retrievals were noticeably larger than radiosonde-based water vapor retrieval during summer 1996. It can explain an overestimation ranging from 5 W/m<sup>2</sup> to 10 W/m<sup>2</sup> in direct horizontal flux and greater values for direct normal flux. So, the water vapor correction factor may explain approximately half of the observed discrepancy between direct modeled and observed fluxes for summer 1996. If the bias between ACR and BSRN/SIROS radiometry is applicable to summer data, it also eliminates discrepancy between modeling and observations from the summer 1996 IOP.

To understand the uncertainties in shortwave flux calculations using different atmospheric transmittance models from LOWTRAN-7 to MODTRAN 3.5, we compared output for these two models. Noticeable changes are only found for the direct component of solar flux.



**Figure 2.** Sensitivity of direct flux component to water vapor and uncertainties in precipitable water for ARM Southern Great Plains (SGP) central facility (CF).

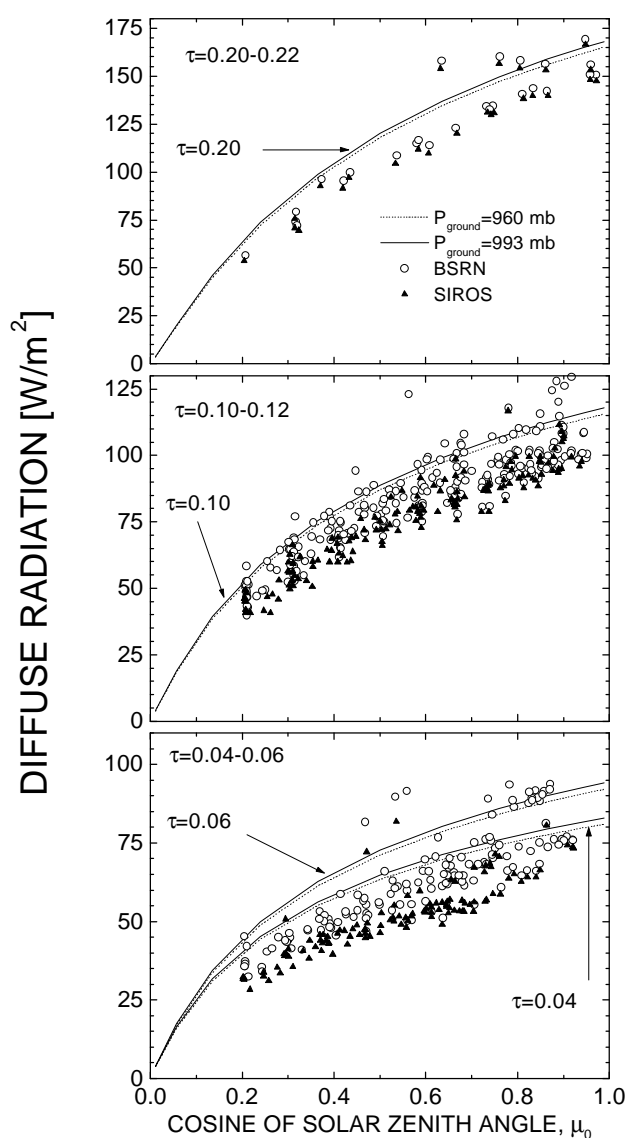
The MODTRAN model is less transparent than LOWTRAN-7. The average difference for ARESE (LOWTRAN-7 minus MODTRAN 3.5) for direct normal flux was found to be  $6.8 \text{ W/m}^2$ , and  $3.0 \text{ W/m}^2$  for direct horizontal flux.

Given the uncertainty in water vapor column amount, the accuracy of radiometer measurement and the uncertainty in the atmospheric transmittance model, the comparisons showed so far for direct flux may be deemed to be in reasonable agreement. However, the comparisons for diffuse flux revealed that on average the modeled values are substantially higher than observed, as first noted by Kato et al. (1997). One possible cause for the discrepancy in diffuse component is the calibration problem, known as negative nighttime bias. At present, the instrument team has not made any recommendation on how to treat this effect. If we assume that the same negative offset exists in the daytime measurements, the disagreement diminishes by  $5 \text{ W/m}^2$  to  $10 \text{ W/m}^2$ .

## Aerosol and Diffuse Flux

To better comprehend the discrepancy in diffuse flux, we analyzed the relation between diffuse flux and AOT measurements from April 1994 to April 1997. The observed and modeled diffuse fluxes for various ranges of

AOT are shown in Figure 3. The WCP-112 continental aerosol model was used together with observed AOT. Minimal and maximal surface air pressure found from the analysis of 3 years of BBSS data were assumed to account for the variation in Rayleigh scattering. Overall, the observed diffuse fluxes are less than model values by about  $10 \text{ W/m}^2$  to  $15 \text{ W/m}^2$ , but one can find many measurements close to model results, as during April 1994. To bring the model values into agreement with observations, we have to use much more absorbing aerosol with low asymmetry factor, unless there exists a systematic bias error in the measurements of diffuse component at the SGP CF site. The latter possibility cannot be totally ruled out.



**Figure 3.** Observed and model estimated surface downward diffuse flux.

For ARESE data, the average SSA in the visible range needs to be reduced to 0.7. However, the hypothesis of such strong absorbing aerosol is not supported by the observation from AOS, which showed a typical range of SSA between 0.85 and 0.95 at 550 nm. Aerosols in the upper troposphere and stratosphere aerosols are more likely to be less absorptive than boundary-layer aerosols.

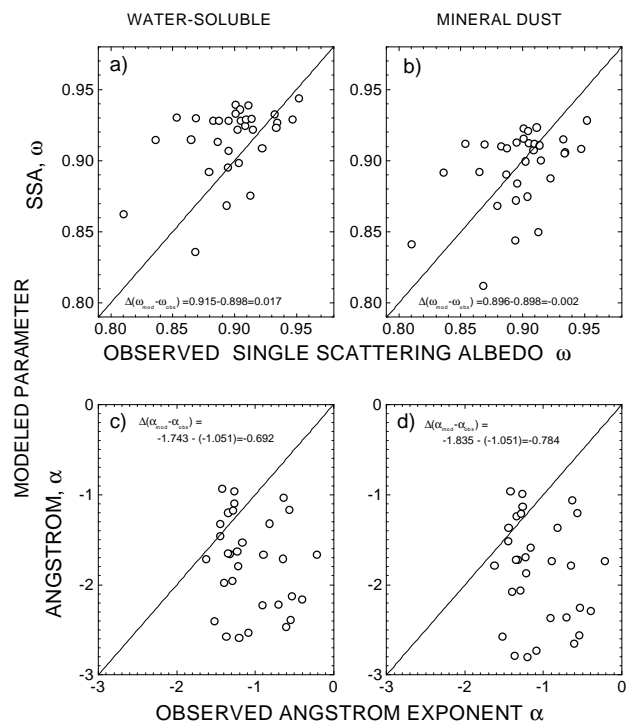
Another source of discrepancy lies in the use of the scalar approach for modeling the transfer of diffuse photons by neglecting the effects of polarization. It can introduce errors in downward diffuse flux up to  $\pm 10\%$ . Although in general it is a relatively small effect (Lacis et al. 1998; Kato et al. 1997), the effect may be important for some specific geometry conditions and surface types that are sensitive to light polarization. The calculation of Rayleigh scattering, albeit suffering from some uncertainties (Bucholtz 1995), is not likely to be responsible for the bias of the magnitude as large as is found here.

## Observed and Simulated Aerosol Properties at the SGP CF

Sensitivity tests of the solar fluxes to various atmospheric constituents show that water vapor and ozone affect mainly the direct component, having almost no effect on the diffuse one. The most important factor altering both direct and diffuse radiation is AOT, followed by aerosol SSA, asymmetry factor and spectral dependence of aerosol extinction determined by the Angstrom exponent. Changes in surface pressure and uncertainties in surface albedo account for a small variation in diffuse radiation.

We modeled aerosol optical properties using synchronous observations from AOS particle counters. Model results for different refractive indices were compared to AOS measurements and MFRSR retrievals. In our calculations of extinction  $\sigma_e$ , SSA  $\omega$ , and asymmetry factor  $g$ , aerosol particles were assumed to be spherical so that we can apply the Mie theory.

The results of the computation for two refractive indices corresponding to mineral dust and water-soluble substances are shown in Figure 4 in comparison with observed values. Despite some scattering, the agreements are rather well. A slightly better agreement was achieved for mineral dust particles.



**Figure 4.** Comparison between observed and simulated aerosol properties.

As for the spectral dependence of the extinction as determined by the Angstrom exponent  $\alpha$ , both models significantly overestimate the absolute values of  $\alpha$ . Note that the observed  $\alpha$  represented the entity of aerosols presented in the entire atmospheric column, while modeled  $\alpha$  was derived from AOS observations made at the ground level.

Cheng (1997) also estimated  $\alpha$  using measurements of the scattering coefficient at AOS for three wavelengths at 450 nm, 550 nm and 700 nm. His estimates varied within the range of -0.9 to -2.7 with an average around -1.74. Monthly averages were between -1.56 and -2.01. Our modeled values are close to those derived by Cheng (1997). Both sets of estimates are systematically lower than observations from the sun photometer measurements and the MFRSR retrievals, which are on average close to -1. The modeled asymmetry factor  $g$  is found to be strongly correlated with the number of sub-micron particles and ranges from 0.25 for a large concentration of sub-micron particles to 0.65 for a small concentration.

## Conclusions

The agreement between modeled and observed solar direct fluxes generally falls within the uncertainties of both modeled and observed fluxes, although the former tends to be larger than the latter.

Our model overestimates diffuse component on average by 15% using a continental aerosol model. To bring model results into agreement with observations requires a much more absorptive aerosol, barring instrumental errors due to calibration, shadowing technique, and spectral or angular response. AOS observations do not support the hypothesis of such a strong absorbing aerosol.

The measurements of aerosol optical properties from the ARM AOS are consistent with Mie theory calculations, but they represent point observations 10 m above the surface level and are not necessarily representative of the entire atmospheric column.

## References

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