Measured and Calculated Solar Radiative Fluxes During SUCCESS: A Sensitivity Study

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Abstract

High accuracy measurements of solar insolation at the surface, made at the U.S. Department of Energy (DOE) Cloud and Radiation Testbed (CART) in Oklahoma, are compared to model calculations with the objective of evaluating the uncertainties in the calculations and observations. In the cases studied, it is found that there is agreement between calculated and measured fluxes within the model and experimental uncertainties. Sensitivities are estimated for variations in optical depth, water vapor profiles, aerosol optical properties and layer thickness, ozone and the presence/absence of undetected, very thin, subvisible cirrus clouds. The aerosol sensitivity calculations are limited to mineral type aerosols. Ranges of modeled values are determined from the sensitivity analysis and are compared to observational data. The experimental uncertainties are evaluated by comparison of the Radiation Measurement System (RAMS) with World Radiation Reference (WRR) absolute cavity/shaded pyranometer combinations.

Introduction

Considerable attention has been focused on radiative processes in the atmosphere because they play a central role in climate. During the last several years, results have been reported indicating poor agreement between the theoretical understanding and experimental results of radiative transfer studies for both cloudless and cloudy atmospheres. Recent studies by Cess et al. (1995), Ramanathan et al. (1995), Pilewskie and Valero (1995, 1996), Zender et al. (1997), and Valero et al. (1997a) conclude that models and observations do not agree on the amount of solar energy being absorbed by the cloudy atmosphere. Furthermore, clear-sky studies by Valero et al. (1996) and Kato et al. (1997) appear to show that model calculations overestimate the insolation in a way that may be consistent with some undefined absorption that is not accounted for in the models. The flux profile observations by Valero et al. (1996) also show, by analyzing the upwelling and downwelling flux profiles, more clear-sky absorption than estimates by models. Kato et al. (1997) use a careful analysis of direct and diffuse radiative fields to conclude that the missing absorption is taking place at visible wavelengths of the solar spectrum and postulate that the unaccounted for absorption must be the result of the presence of an unknown gas in the atmosphere.

In summary, the current understanding of the atmospheric radiative processes for clear and cloudy conditions has been questioned to various degrees (Fritz et al. 1951; Stephens and Tsay 1990; Ramanathan et al. 1995; Cess et al. 1995; Pilewskie and Valero 1995 and 1996; Arking 1996; Connant et al. 1997; Zender et al. 1997; and Valero et al. 1997a). The proper study of the above issues requires additional observational and modeling efforts directed toward the radiative processes in the atmosphere and their relationship with aerosols and clouds.

In this paper, we summarize the results of comparing highly accurate flux measurements with model calculations. The accuracy of the flux measurements is determined by comparison with the WRR. The sensitivity of the calculations to the experimental errors in the measurement of the input parameters (optical depth, water vapor profiles, etc.) is evaluated and a model uncertainty is thus determined. Such model uncertainty is used to estimate a range of calculated values, which is then compared to the measurements including the experimental error.

Surface Irradiance Measurements

This work concentrates on surface-based observations that were made at the CART site in Oklahoma during the National Aeronautics and Space Administration (NASA)-sponsored Subsonic Aircraft Contrail and Clad Effects Special Study (SUCCESS) project, which occurred simultaneously with the April 1996 CART Intensive

Observation Period (IOP). For the observations in this study, we used part of the RAMS that is a multiple instrument array of radiometric sensors (Valero et al. 1997b; Bush et al. 1998). Two of the instruments comprising the RAMS package are the total solar broadband radiometer (TSBR) with a spectral bandpass from 0.225 to 2.7 microns and a total-direct-diffuse radiometer (TDDR) with seven narrowband (10-nm) channels at 500 nm, 862 nm, 1062 nm, 1250 nm, 1550 nm, 1650 nm, and 1750 nm. In addition to the RAMS radiometers, direct solar flux measurements were made with two absolute cavity instruments traceable to the WRR. The absolute cavity radiometers as well as selected shaded pyranometers were supplied by the Surface Radiation Research Branch (SRRB) of the National Oceanic and Atmospheric Administration (NOAA) (Michalsky et al. 1997). Excellent agreement (within a few W/m^2) between the RAMS and SRRB instruments (combination of direct cavity and diffuse pyranometer measurements) was observed. Also utilized in the data and model comparisons are the corresponding Solar and InfraRed Observation Stations (SIROS) and Baseline Solar Radiation Network (BSRN) measurements. These total downwelling fluxes are computed using the component summation method described above; however, the direct beam term is determined from a normal incidence pyrheliometer (NIP) rather than an absolute cavity.

Optical Depth Measurements

Optical depths were determined using measurements from the TDDR. The measured total optical depth is decreased by the Rayleigh scattering optical depth to infer the “aerosol” optical depth (which also contains contributions from cirrus clouds, if present). It is this optical depth from the 500-nm TDDR channel that is used specifically to drive the model calculations by normalizing the dust aerosol spectral profile at this wavelength.

Model Calculations

All model calculations were made using the Moderate Resolution Transmittance (model) (MODTRAN) (Anderson et al. 1995) atmospheric transmission model using the discrete ordinate radioactive transfer (DISORT) (Stamnes et al. 1988) radiative transfer code. For each model simulation, a realistic atmospheric profile was formulated using radiosonde measurements of pressure, temperature, and humidity. Individual molecular species profiles were obtained from the MODTRAN midlatitude summer standard atmospheric profile. Extinction, absorption, and asymmetry parameters corresponding to a desert summertime aerosol were used to characterize the aerosol type. Optical depths used to regulate the aerosol content in the model simulation were obtained via measurements by the TDDR.

All model calculations presented in this paper are for surface fluxes at the DOE’s CART site located in northern Oklahoma. For each simulation, the direct solar and diffuse components are calculated separately and then combined to obtain the total downwelling flux. Specific instrument responses (TSBR, TDDR 500 run, and TDDR 862 nm) are simulated via integrations over appropriate spectral bandpasses. In the cases of “time marching” calculations, model values are determined every 10 minutes with intermediate values resulting from a cubic spline interpolation.

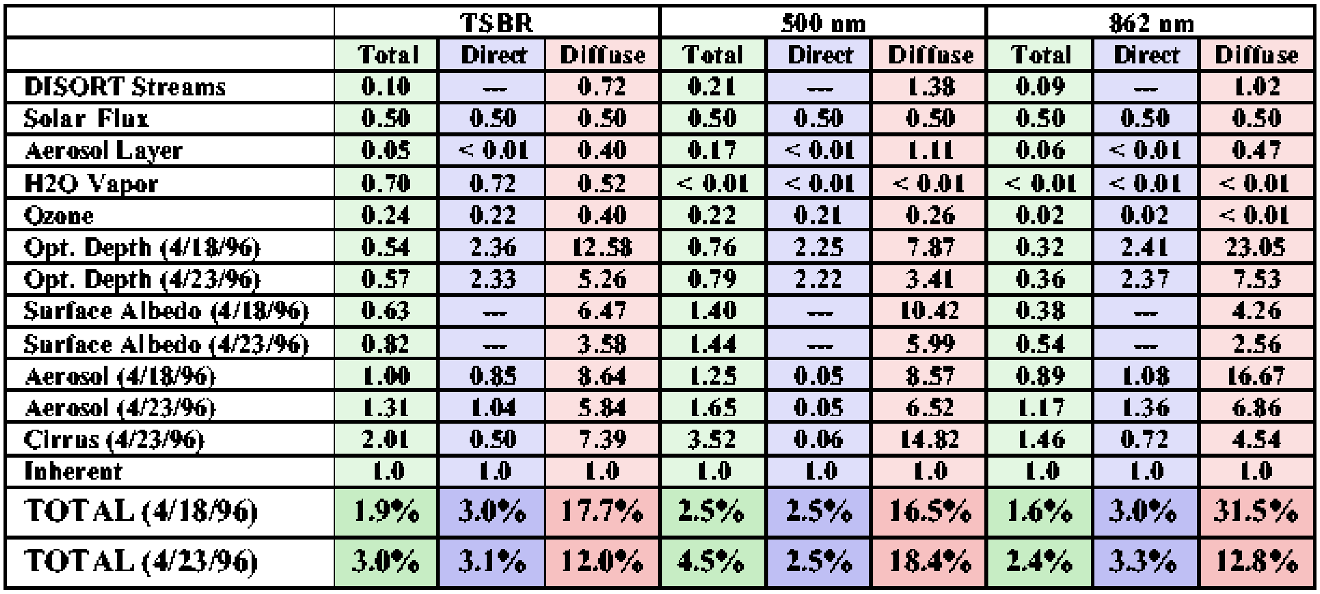
Sensitivity Study

Because the model itself and all of the model input parameters are subject to inherent and/or experimental errors, it is important to complete a sensitivity study with respect to each of these parameters to be able to describe their individual effects on the final flux determinations. This sensitivity study included varying the following parameters: 1) number of streams used in the DISORT routine, 2) solar irradiance profiles, 3) aerosol layer thickness, 4) total atmospheric water vapor content, 5) 500-nm aerosol optical depth, 6) atmospheric ozone content, 7) surface albedo variations, 8) thin or subvisual cirrus effects, and 9) mineral aerosol type. In addition to uncertainties in some of the physical parameters listed above and other basic model input parameters, the intrinsic uncertainty (resulting from parameters “ inaccessible” to the user, approximations, etc.) of the model is estimated with a lower limit of approximately 1%. Important additional sources of uncertainties in the calculated fluxes that are not completely accounted for here, result from poor knowledge of aerosol optical properties, composition and microphysics.

Summary of Sensitivity Results

The complete sensitivity results are summarized in Table 1. Model uncertainties are determined for the April 18 and 23 cases separately. Variations in absolute percentage uncertainties result from the differing atmospheric conditions existing on these days. Even though the percentage differences are higher for the diffuse components compared to the direct or total downwelling fluxes, the approximate magnitude (in W/m^2) is roughly the same. The case on April 23 also has an additional uncertainty due to the presence of thin or sub-visual cirrus that is apparently absent on April 18.

Table 1. MODTRAN clear-sky uncertainties. A summary of the clear-sky sensitivity study. The total (green), direct (blue), and diffuse (red) uncertainties are given for each spectral region as well as for each model input parameter. The optical depth, surface albedo, and aerosol effects are separated for April 18 and 23. An uncertainty due to thin or sub-visual cirrus is also included for April 23. The percent uncertainties are larger for the diffuse signal because its magnitude is typically 5 to 10 times less than the total or direct terms. The absolute uncertainties in W/m^2 are all comparable. (For a color version of this table, please see *http://www.arm.gov/docs/documents/technical/conf_9803/bush-98.pdf*.)



	TSBR			500 nm			862 nm		
	Total	Direct	Diffuse	Total	Direct	Diffuse	Total	Direct	Diffuse
DISORT Streams	0.10	—	0.72	0.21	—	1.38	0.09	—	1.02
Solar Flux	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
Aerosol Layer	0.05	< 0.01	0.40	0.17	< 0.01	1.11	0.06	< 0.01	0.47
H2O Vapor	0.70	0.72	0.52	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01
Ozone	0.24	0.22	0.40	0.22	0.21	0.26	0.02	0.02	< 0.01
Opt. Depth (4/18/96)	0.54	2.36	12.58	0.76	2.25	7.87	0.32	2.41	23.05
Opt. Depth (4/23/96)	0.57	2.33	5.26	0.79	2.22	3.41	0.36	2.37	7.53
Surface Albedo (4/18/96)	0.63	—	6.47	1.40	—	10.42	0.38	—	4.26
Surface Albedo (4/23/96)	0.82	—	3.58	1.44	—	5.99	0.54	—	2.56
Aerosol (4/18/96)	1.00	0.85	8.64	1.25	0.05	8.57	0.89	1.08	16.67
Aerosol (4/23/96)	1.31	1.04	5.84	1.65	0.05	6.52	1.17	1.36	6.86
Cirrus (4/23/96)	2.01	0.50	7.39	3.52	0.06	14.82	1.46	0.72	4.54
Inherent	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
TOTAL (4/18/96)	1.9%	3.0%	17.7%	2.5%	2.5%	16.5%	1.6%	3.0%	31.5%
TOTAL (4/23/96)	3.0%	3.1%	12.0%	4.5%	2.5%	18.4%	2.4%	3.3%	12.8%

Conclusions

The model calculations are compared to the measured quantities in Figure 1 for April 18. The total downwelling flux is given by the TSBR measurement for the total solar bandpass and the direct and diffuse components are taken from the SIROS/BSRN measurements from the NIP and shaded pyranometers. The various shaded bands indicate the model calculations along with the associated uncertainties as summarized in Table 1.

The comparison of calculated and observed insolations indicate, in general, marginal agreement. The measured and calculated values are within the range of values determined when uncertainties are taken into account. There is, however, a characteristic that is common to most observations (Valero et al. 1996, Kato et al. 1997, Zender et al. 1997); there is a persistent bias even within the error margins of models towards values larger than observed. Such bias is relatively small in some cases (i.e., Zender et al. 1997) and larger in others (Kato et al. 1997). The observed biases suggest, in particular after analyzing the diffuse radiation fields, that it is possible that some unknown absorber may be present in the atmosphere. On the other hand, to reach such a conclusion, one needs to clearly establish and reduce the margins of uncertainties in calculated and measured parameters. It appears that a possible major improvement in this situation would result from more accurate characterization of aerosols optical properties and composition. Additionally, the measurement of optical depths above and below aerosol layers would help identify and quantify the effects of aerosols separately from those of overlying cirrus.

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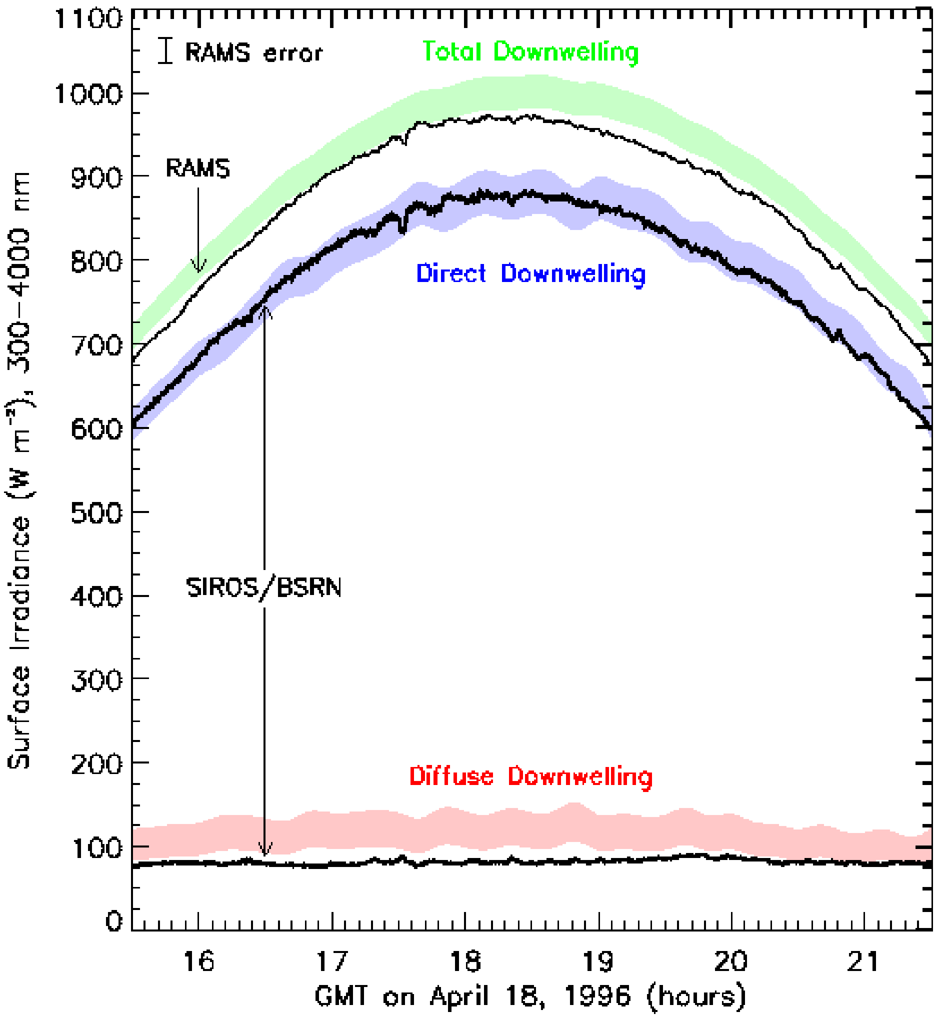

Figure 1. Comparison of the model simulations with error bars and the measured quantities on April 18, 1996. The RAMS data is from the TSBR for the total solar bandpass. The SIROS/BSRN data are from the NIP instrument for the direct beam and shaded pyranometer for the diffuse. (For a color version of this figure, please see *http://www.arm.gov/docs/documents/technical/conf_9803/bush-98.pdf*.)

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