Diffuse-Sky Downward Irradiance (DFDI) at Surface in Cloud-Free Atmospheres - A Closure Experiment

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Abstract

Radiative transfer models consistently overestimate surface diffuse downward irradiance (DFDI) in cloud-free atmospheres by 9% to 40% at two low altitude sites while correctly calculating direct-normal solar irradiance (DNSI). Of the 32 independent cases analyzed, the amount of over-estimation is found to be larger than the combined uncertainties in model inputs, model calculations, and measured DFDI. But models correctly calculate the DNSI. For realistic aerosol optical properties, the only way to reconcile these findings is to reduce sunphotometer-inferred aerosol optical thickness (AOT) by an average 0.022 ± 0.01 at 550 nm, while at the same time increasing continuum-like atmospheric absorptance over the solar spectrum by an average 5% ± 3%. At two high-altitude sites, models and measurements agree to within their mutual uncertainties, suggesting that this phenomenon is present only in the boundary layer. The proposed excess absorption and corresponding reduction in AOT would have important consequences for climate and remote sensing.

Introduction

In an earlier study (Halthore et al. 1997), a model calculation of DNSI, the energy falling on unit surface normal to sun's direction in unit time, was found to be well within 1% of measurements at the Atmospheric Radiation Measurement (ARM) Southern Great Plain (SGP) site. The closure in DNSI indicates that 1) the atmospheric transmittance was accurately measured by sunphotometers in narrow spectral bands throughout the visible and near-infrared (IR); 2) the models correctly extended the measured transmittance between and beyond the sunphotometer channels, taking into account shortwave gaseous band absorption in the atmosphere; and 3) the extraterrestrial solar irradiance was accurately represented in the models. The model used, moderate resolution atmospheric radiance and transmittance model (MODTRAN) 3.5, is a medium (2 cm^{-1}) resolution radiative transfer code that uses band models based on HITRAN data base. Here, we describe a closure experiment that compares measured and modeled DFDI at the surface. DFDI is the energy falling on a unit area of a horizontal detector per unit time from the hemispherical sky with the sun blocked by a shading device. Instruments that measure DFDI are called shaded precision spectral pyranometers (PSPs). As with DNSI, DFDI depends on the extra-terrestrial solar irradiance and atmospheric transmittance; but in addition, it also depends on the scattering properties of the atmospheric constituents—molecules and aerosols. Rayleigh or molecular scattering is a well known process and can be accurately estimated by measuring the surface pressure or altitude. On the other hand, aerosol scattering properties of spectral single scattering albedo (SSA, ratio of scattering to total attenuation) and spectral phase function (probability of scattering into a given direction) depend on aerosol composition and size distribution as a function of height and are a lot more difficult to measure. A reliable DFDI measurement requires uniform cosine response of the detector for light incident at different angles. A further complication in DFDI measurement arises from the difficulty in calibrating PSPs at the light levels typical of DFDI on cloud-free days. Their calibration at high light levels, without the shade, is extrapolated to lower light levels. The calibration process is not as straightforward as that for the normal incidence pyreheliometers (NIPs) or cavity radiometers (used to measure DNSI). For all these reasons, a comparison of measured and modeled DFDI constitutes a closure experiment that is not as robust as that of DNSI. However, below we describe a closure experiment in DFDI which shows that the models overestimate the measurements in all cases at two low altitudes by an amount that exceeds the combined estimates of uncertainties in model input quantities and measurements. At two high-altitude sites, the models correctly calculate DFDI.

Models and Measurements

Data from instruments at two low-altitude sites in north central Oklahoma (SGP Site, 36.605 N, 97.485 W, 319 m altitude) and north central Canada [Boreal Ecosystem-Atmosphere Study (BOREAS), 53.92 N, 104.69 W, 510.5 m altitude; 53.90 N, 106.1 W, 550 m altitude] were used along with data from two high-altitude sites at Mauna Loa, Hawaii Observatory (MLO, 19.533 N, 155.578 W, 3,400 m altitude) and at the Amundsen-Scott South Pole Base in Antarctica (SPO, 89.98 S, 24.8 W, 2,800 m altitude). Data from periods in 1994 to 1997 are available. Thirty-five independent comparisons were made. Clear skies are determined by inspection of DFDI in relation to the total downward irradiance as measured by unshaded PSP. Two different broadband models (MODTRAN 3.5 and 6S) employing three different multiple scattering schemes (2-Stream Issacs model, discrete ordinate method for MODTRAN and Method of Successive Order of Scattering for 6S) are used.

Sunphotometer-measured AOT and radiosonde-measured pressure, temperature and relative humidity as a function of height are used as inputs to the models. Additional inputs included SSA and asymmetry parameter, which were measured at the surface, at SGP by an integrating nephelometer and a particle absorption photometer. The procedure for the closure experiment involved running MODTRAN in the transmittance mode to obtain sunphotometer-observed transmittance, then running the model in the DNSI mode to check for pyrheliometer (or cavity radiometer) measured DNSI and finally running the MODTRAN in flux mode to obtain DFDI. MODTRAN is run in both 2-stream mode and in 8-stream mode. The output of 6S provides both DNSI and DFDI at the surface in a single run.

Results and Discussion

The three models calculate DFDI to within 1 W m^{-2} of each other (see Table 1). For all low-altitude cases, Figure 1, (29 cases at SGP, 3 at BOREAS), model estimates are higher than measurements. For all high-altitude cases (3 cases), models correctly calculate DFDI. For one of the cases in Figure 1, a sensitivity analysis is performed as summarized in Table 1, to study the effect on the model overestimation. Measurements, given in row 1, are for September 27, 1997, at the SGP site, 1722 UT, 40.29° solar zenith angle. For the base case, rows 2 - 4, the three models agree to within 1 W m^{-2}.

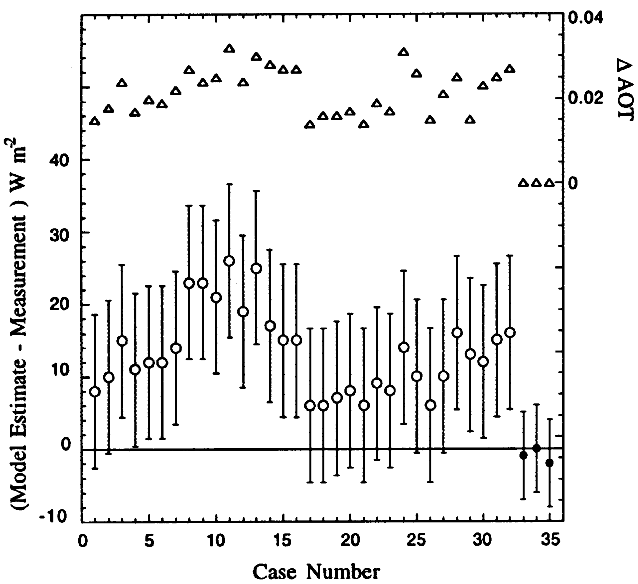

Figure 1. Plot of DFDI (model - measurement) for each of the 35 cases examined. Low-altitude cases (1-29, SGP; 30-32, BOREAS; open circles) have error bars ± 10.6 W m^{-2} representing uncertainties in model inputs and measurements. High-altitude cases (33 and 34, MLO; 35, SPO; solid circles) exhibit smaller error bars (±6 W m^{-2}) because AOT was not employed in the calculations. Reduction in apparent AOT, DAOT, required to close the gap between model estimates and measurements, is also shown (triangle).

From the last column in Table 1, it is clear that SSA of 0.5 or AOT of 0.03 (a reduction of 0.03 from a measurement of 0.06) can close the gap. SSA of 0.5 cannot be justified in the light of its measured value of 0.86 and reduction in AOT of 0.03 is three times its uncertainty of 0.01. Simultaneous

Table 1. Sensitivity of DFDI to aerosol and surface optical properties.

Method	Surface Reflectance	SSA	Asym. Param.	AOT at 550 nm	DFDI W m^{-2}	ΔDFDI W m^{-2}
Measured	Green grass[(a)] (sw albedo=0.20)	0.86[(b)]	0.6[(c)]	0.06	68[(d)]±8	
2 Stream	Green grass	0.86	0.6	0.06	84	16
3 Stream	Green grass	0.86	0.6	0.06	84	16
6S	Green grass	0.86	0.65	0.06	85	17
2 Stream	**0.2 (constant)**	0.86	0.6*	0.06	87	19
2 Stream	**0.1**	0.86	0.6	0.06	84	16
2 Stream	**0.0**	0.86	0.6	0.06	80	12
2 Stream	Green grass	**1.0**	0.6	0.06	91	23
2 Stream	Green grass	**0.7**	0.6	0.06	77	9
2 Stream	Green grass	**0.5**	0.6	0.06	68	0
2 Stream	Green grass	**0.3**	0.6	0.06	59	-9
2 Stream	Green grass	0.86	**0.3**	0.06	82	14
2 Stream	Green grass	0.86	**0.0**	0.06	72	4
2 Stream	Green grass	0.86	0.6	**0.05**	79	11
2 Stream	Green grass	0.86	0.6	**0.03**	68	0

Varied quantities are in **bold** type.
(a) Spectral albedo was measured at a similar site in Kansas.
(b) Variability is about ±0.03.
(c) Deduced from measured backscattering/scattering ratio.
(d) Measured value of 60 W m^{-2} was augmented by 1 W m^{-2} for aureole correction and 6.5 W m^{-2} for nighttime offset correction. The 95% confidence limit in this measurement is ±8 W m^{-2}. A second independently calibrated instrument gave a value 69 W m^{-2}.

reduction in SSA, asymmetry parameter, and AOT to 0.7, 0.4 and 0.05, respectively, can close the gap, but these values are unlikely and/or unrealistic, based on our knowledge of aerosol properties and their measurement uncertainties. Thus, here we establish that modeled DFDI can be brought into agreement with measured DFDI only by extreme and/or unrealistic values of input parameters. The combined uncertainty in the model estimation due to uncertainties in each of the above varied quantities is calculated as 9.3 W m^{-2} where the uncertainty in each quantity is considered as uncorrelated with the others. Based on our knowledge of the measurements, we consider uncertainty in measurements to be ±8 W m^{-2} at the 95% confidence level and 5 W m^{-2} at the 75% confidence level. The resulting combination of modeled and measured uncertainties in the quantity (DFDI model - DFDI meas) is calculated as 12.3 W m^{-2} or 10.6 W m^{-2} at the 95% and 75% confidence level, respectively. It is the latter value that is plotted in Figure 1, which shows that there are 20 cases out of 32 that depict a clear model overestimation. Even at the 95% confidence level, there are 16 cases out of 32 that show a clear model overestimation.

Reduction in sunphotometer inferred AOT (apparent AOT, hereafter) is most effective in bringing the model estimates closer to measurements (Table 1). However, apparent AOT cannot be arbitrarily reduced beyond its uncertainty (0.01 at airmass of 1) as the models using this apparent AOT calculate measured DNSI accurately. Thus, a reduction in apparent AOT must be accompanied by an increase in atmospheric absorption (Kato et al. 1997). For each of the 32 low-altitude cases, we computed the required reduction in AOT, DAOT, to close the gap (Figure 1). The uncertainty in the value of apparent AOT of 0.01 dominates the uncertainty in DAOT calculated here to be ±0.014. The average value for all 32 cases is 0.022 corresponding to 60° slant path value of 0.044. The increase in atmospheric absorptance is therefore ~4.8%, including the effect of surface reflected flux. The uncertainty in this value is ~±3%. Both models currently have about 21% atmospheric absorptance for a mid-latitude summer atmosphere and for a surface reflectance of 0.1. The proposed increase would bring this value closer to 26% ±3%. This is a substantial increase that would affect all shortwave budget studies and climate prediction.

The proposed reduction in apparent AOT of 0.022 would have an impact on aerosol climatology and atmospheric correction of remotely sensed data, including satellite sensor calibration. Is there evidence to support the ubiquitous presence (at low altitudes) of additional atmospheric absorption of optical thickness ~0.022 in the sunphotometer data? Figure 2 shows a histogram of over 80,000 values of apparent AOT at 440 nm obtained from accurately calibrated Cimel sunphotometers located at widely dispersed points in Africa and Western Hemisphere (from AERONET). Of these 80,000 values obtained in the period from 1993 to present, not one value was found to be below 0.02. The observed sunphotometer-inferred AOT data is thus consistent with the excess absorption hypothesis on the assumption that truly aerosol-free conditions should be occasionally encountered.

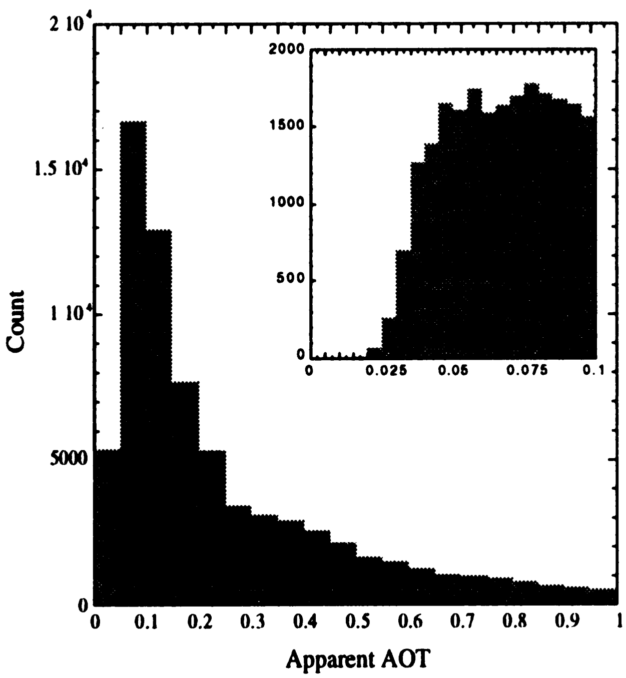

Figure 2. Histogram of 80,000 values of AOT at 440 nm inferred from sunphotometer measurements at 5 locations around the world. About 10,000 measurements in Eastern U.S., 10,000 in mid-continental Canada, 32,000 in Western U.S., 12,000 in Brasilia, Brazil, and 16,000 in Western Sahara are shown here spanning a period from 1993 to present. The period considered here exhibits minimum influence of stratospheric aerosols from volcanic eruptions. The data are obtained from calibrated sunphotometers (accuracy ~0.01/m, where m is the airmass) maintained by AERONET.

Conclusions

This study has shown that current atmospheric radiative transfer models overestimate DFDI at the surface under cloud-free skies, and that in the absence of unrecognized systematic errors in the measured DFDI, the gap between modeled and measured DFDI cannot be closed for realistic aerosol optical properties. Earlier work had shown (Halthore et al. 1997) that the DNSI is correctly calculated by models that use measured atmospheric attenuation. The only way to reconcile these findings is to reduce what has been traditionally interpreted as AOT in sunphotometeric measurements, by 0.015 to 0.03, with a corresponding increase in atmospheric absorptance (currently ~21% in these models) by an average of about 5%. These findings apply to the boundary layer but not to high altitudes, where models correctly calculate DFDI. The amount of reduction in AOT with a corresponding increase in atmospheric absorption proposed here would have important consequences for many areas of earth-atmospheric radiative transfer including aerosol climatology, remote sensing, and climate prediction.

Acknowledgments

MLO data was obtained from the National Oceanic and Atmospheric Administration (NOAA) Climate Monitoring and Diagnostics Laboratory (CMDL) observatory. SPO data were obtained from the Baseline Surface Radiation Network (BSRN) data archive maintained by ETH World Radiation Monitoring Center. BOREAS data were obtained from the BOREAS data base maintained at the National Aeronautics and Space Administration (NASA)/Goddard Space Flight Center (GSFC). Cloud and Radiation Testbed (CART) SGP data were obtained from the ARM Program sponsored by the U.S. Department of Energy (DOE). Sunphotometer data were obtained from AERONET, managed by B. N. Holben, NASA/GSFC. 6S was made available by E. Vermote, NASA/GSFC. G. P. Anderson (Air Force Research Laboratory, Hanscom AFB, Massachusetts) is acknowledged for consultations throughout the course of this work. Work at Brookhaven National Laboratory was supported by the Environmental Sciences Division of the DOE as part of the ARM Program and was performed under the auspices of DOE under Contract No. DE-AC02-98CH10886.

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