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Models overestimate diffuse clear-sky surface irradiance: A case for excess atmospheric absorption

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Abstract. Radiative transfer models consistently overestimate surface diffuse downward irradiance in cloud-free atmospheres by 9 to 40% at two low altitude sites while correctly calculating direct-normal Solar irradiance. For known systematic and random measurement errors and for realistic aerosol optical properties, the discrepancy can be resolved by a reduction in the vertical aerosol optical thickness (AOT) inferred from sunphotometric measurements by an average 0.02 ± 0.01 for 32 cases examined, together with a compensating increase in a continuum-like atmospheric absorptance over the solar spectrum of ~5.0% ± 3.0%. This phenomenon is absent at two high altitude sites, where models and measurements agree to within their mutual uncertainties. Examination of apparent AOT at several locations around the globe also indicates presence of such excess atmospheric absorption. The proposed absorption and corresponding reduction in AOT would have important consequences for climate prediction and remote sensing.

Introduction

Model calculations of diffuse downward irradiance at the surface, DFDI, the energy incident per second from the hemispherical cloud-free sky on a horizontal surface, exceed measured values; the same models correctly compute the direct normal solar irradiance at the surface, DNSI, the solar energy incident on a per unit time on a unit area of the surface normal to the direction to the Sun [*Kato et al.*, 1997; *Halthore et al.*, 1997a, b]. The closure in DNSI indicates that (i) the atmospheric transmittance was accurately measured by sunphotometers in narrow spectral bands throughout the visible and near-IR; (ii) the models correctly extended the measured transmittance between and beyond the sunphotometer channels taking into account estimates of shortwave gaseous band absorption in the atmosphere; and (iii) the extraterrestrial solar irradiance was accurately represented in the models. Because DFDI is dependent on scattering by molecules and aerosols whereas DNSI is dependent on the overall extinction, it was conjectured by *Kato et al.* that the aerosol optical thickness (AOT) as inferred by sunphotometers may have been overestimated and therefore that a reduction in this apparent AOT may be necessary to reduce model estimates of DFDI, with a compensating increase in atmospheric absorption to conserve DNSI. Here we report results of a systematic comparison between modeled and measured DFDI involving data from four different sites and using two different broad-band models employing three different multiple scattering schemes. Thirty five independent, instantaneous, comparisons each designated as a case and each pertaining to a unique set of atmospheric and radiative properties, were made at these four sites. In addition, data obtained from a worldwide network of sunphotometers were used to obtain independent supporting evidence for the excess atmospheric absorption.

Measurements and Models

Measurements from four locations are employed — North-Central Oklahoma (SGP, Southern Great Plains Site, 36.605 N, 97.485 W, 319 m altitude), North-Central Canada (BOREAS, 53.92 N, 104.69 W, 510.5 m altitude; 53.90 N, 106.1 W, 550 m altitude), 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).

DFDI was measured using a shaded pyranometer (precision spectral pyranometer, or PSP, Eppley Laboratory Inc.) consisting of a horizontal thermopile detector enclosed in a glass envelope that transmits in the shortwave (0.29 - 2.8 μm). Shading the sensor from direct Sun light with a mechanical device such as a metal band or a disk which tracks the Sun, permits measurement of DFDI (Wm^{-2}). PSPs are calibrated at high energy levels in the unshaded mode with reference to devices whose calibration can be traced to World Radiation Reference standard at Davos, Switzerland. The nominal accuracy of a measurement is typically ±5%. However, at low energy levels linearity of the instruments, a maximum of 0.5% of full scale (i.e., 7 Wm^{-2}), dominates the uncertainty, estimated at 95% confidence level to be ±8 Wm^{-2} (5 Wm^{-2} at 75% confidence level). At the SGP, measurements by two pyranometers generally agreed to within 2% (1 Wm^{-2}). In most cases horizontal alignment was checked periodically and shadow bands were adjusted weekly [*Shewchuk*, 1997]. The data are corrected for the observed nighttime negative bias (-5 to -8 Wm^{-2}) in these

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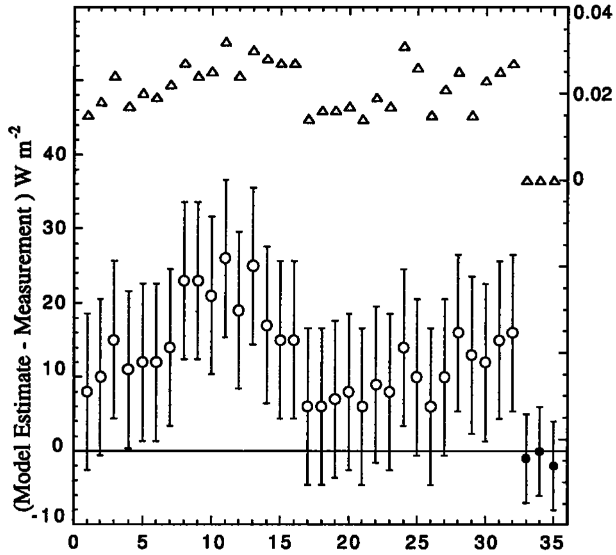

Figure 1. Plot of $\Delta DFDI$ (model - measurement) for each of the 35 cases examined. Low altitude cases (1–29, SGP; 30–32, BOREAS; open circles) have error bars $= \pm 10.6\ Wm^{-2}$ representing uncertainties in model inputs and measurements. High altitude cases (33 and 34, MLO; 35, SPO; solid circles)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

instruments as the bias represents, in the opinion of many, a flux from the instrument to the sky that is present during day as well. All measurements are increased to correct for the blockage of the Solar aureole by a small amount, usually $\sim 1\ Wm^{-2}$, except at BOREAS, $\sim$ 10% or 4 Wm^{-2}, where a shadow band was used.

Supporting measurements include radiosonde-measured vertical profiles of pressure, temperature and relative humidity, sunphotometer-measured column averaged atmospheric extinction in seven narrow bands (full width 10 nm) in the visible and near IR [*Holben et al.*, 1998] and water column abundance in the 940 nm band [*Halthore et al.*, 1997c], aerosol total- and back-scattering coefficient and absorption coefficient at surface at SGP, and DNSI measurements at the SGP, MLO and SPO sites. Experiments were performed close to radiosonde launch times whenever possible. Absence of clouds was determined by visual inspection of the sky and/or by examination of the time traces of DFDI and total downward irradiance. Data span a period from 1994 (BOREAS), through 1995 (SPO), 1996 and 1997 (SGP and MLO). A wide range of Solar zenith angles, from 30°to 82°, PW, from 0.1 cm on Mauna Loa to 0.77 cm in BOREAS and 4.3 cm in SGP, and AOT at wavelength $\lambda = 550$ nm, from 0.03 at BOREAS to 0.26 at SGP, are used in this analysis. BOREAS measurements were made at two sites separated by about 100 km, with exceptionally clear skies over both sites.

DFDI is computed using MODTRAN3.5 (V. 1.5) [*Bernstein et al.*, 1996; *Berk et al.*, 1998; *Wang et al.*, 1996] and 6S (V. 4.1) [*Vermote et al.*, 1997] both with a resolution of 2 cm^{-1}. Both models include absorption by CO_2, H_2O, O_2 and other minor gases. For solving the transfer equation, MODTRAN employs a 2-stream method based on Issacs model and a multiple stream discrete-ordinate method; 6S uses the method of Successive Order Approximation. AOT was specified either directly (6S) or by specifying horizontal visibility (MODTRAN). In the absence of measurements SSA was assumed to be 0.94 (at 550 nm). Spatially uniform Lambertian surfaces were used in both models. Surface albedo for the four sites came from other sources — [*Walter-Shea et al.*, 1992] for SGP; [*Betts and Ball*, 1997] for BOREAS; 0.82 (constant) in the visible and near-IR for SPO; and 0.05 (constant) for MLO. Each model simulation involves first a run in the "transmission" mode to reproduce AOT inferred from sunphotometer measurements, followed by a run in the "direct Solar irradiance" mode to check DNSI and finally run in the "flux" mode to calculate DFDI. For 6S, DNSI and DFDI are computed in a single run.

Results

Examination of results for the 35 comparisons in Figure 1 reveals that modeled DFDI consistently exceeds measured except at the high altitude MLO and SPO sites. For the low altitude cases the discrepancy expressed as a fraction of the measured DFDI is 12% – 28% and expressed as a fraction of top of the atmosphere (TOA) Solar irradiance is 1.4% – 2.8%. There is no clear correlation of fractional deviation with airmass, AOT, or PW. In contrast to the low altitude data, the MLO and SPO data show no significant discrepancy between models and measurements for both DNSI and DFDI; SPO data were simulated for a standard atmosphere with AOT = 0. The agreement between measured and modeled DFDI in these cases suggests that lack of treatment of polarization in the models is unimportant [*Lacis et al.*, 1998].

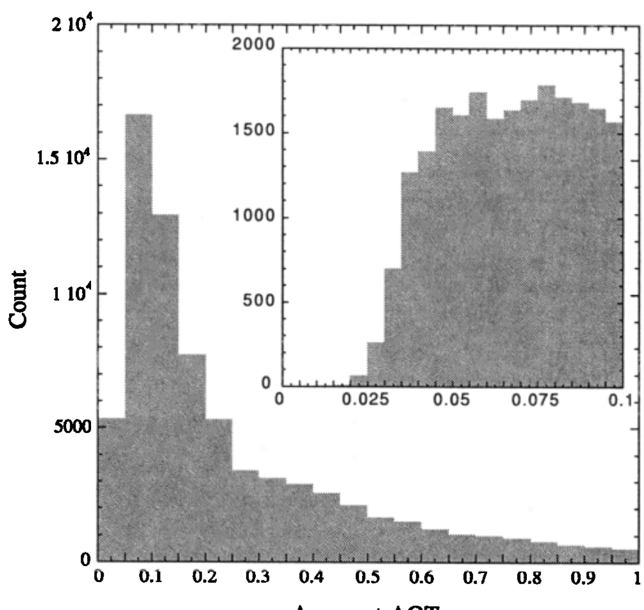

Figure 2. Histogram of 80,000 values of AOT at 440 nm inferred from sunphotometer measurements at 5 locations around the world. About 10,000 measurements in the Eastern U.S., 10,000 in Mid-continental Canada, 32,000 in Western U.S., 12,000 in Brasilia, Brazil, and 16,000 in Western Sahara are shown here 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 at airmass 1) maintained by AERONET [*Holben et al.*, 1998].

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

Meth.	Surf. Refl.	SSA	Asym. Param.	AOT 550 nm	DFDI Wm^{-2}	ΔDFDI Wm^{-2}
Meas.[a]	Veg.[b]	0.86[c]	0.6[d]	0.06	68[e]±8	
2 Str.	Veg.	0.86	0.6	0.06	84	16
8 Str.	Veg.	0.86	0.6	0.06	84	16
6S	Veg.	0.86	0.65	0.06	85	17
2 Str.	**0.2**[f]	0.86	0.6	0.06	87	19
2 Str.	**0.1**[f]	0.86	0.6	0.06	84	16
2 Str.	**0.0**[f]	0.86	0.6	0.06	80	12
2 Str.	Veg.	**1.0**	0.6	0.06	91	23
2 Str.	Veg.	**0.7**	0.6	0.06	77	9
2 Str.	Veg.	**0.5**	0.6	0.06	68	0
2 Str.	Veg.	**0.3**	0.6	0.06	59	-9
2 Str.	Veg.	0.86	**0.3**	0.06	82	14
2 Str.	Veg.	0.86	**0.0**	0.06	72	4
2 Str.	Veg.	0.86	0.6	**0.05**	79	11
2 Str.	Veg.	0.86	0.6	**0.03**	68	0

Varied quantities are in **bold** type. (a) Measurements are for Sep. 27, 1997 at SGP, 1722 UT, 40.29°solar zenith angle. (b) Spectral albedo of vegetation (0.2 over the shortwave spectrum) was measured at a similar site in Kansas. (c) Variability is about ±0.03. (d) Deduced from measured backscattering / scattering ratio. (e) Measured value of 60 Wm^{-2} was augmented by 1 Wm^{-2} for aureole correction and 6.5 Wm^{-2} for nighttime offset correction. A second instrument measured 69 Wm^{-2}. (f) Constant across solar spectrum.

Measurements performed on September 27, 1997 at the SGP site at 1722 UT at a Solar zenith angle of 40.29° form the basis of a sensitivity analysis (Table 1) to determine the effect of model inputs on DFDI estimates. Row 1 in Table 1 summarizes measured values. A base case (rows 2 - 4) is taken as a surface covered by green vegetation with shortwave albedo $\simeq$ 0.2, aerosol single scattering albedo (SSA) 0.86, and aerosol asymmetry parameter (AP) 0.6 deduced [*Marshall et al.*, 1995] from a measurement of back to total scattering ratio of 0.17. The AOT at 550 nm inferred from sunphotometer measurements was 0.06 with Ångström exponent ($-d\ln(AOT)/d\ln\lambda$) 1.5. All three models calculate DFDI to within 1 Wm^{-2}, and all exceed by about 23% or 16 Wm^{-2} the measured value of 68 Wm^{-2} ± 8 Wm^{-2}. By varying parameters one at a time, the difference between modeled and measured DFDI is computed and given in the last column of Table 1. An extreme case of zero surface reflectance, which is clearly unrealistic, yielded 4 Wm^{-2} lower. Decrease of SSA to 0.5, a value far below the measured 0.86, was necessary to close the gap between modeled and measured values. Measurements at SGP and other work [*Haywood and Shine*, 1995] show that such a low value is unrealistic for aerosols in natural ambient air in rural areas. A decrease of AP to a similarly unrealistic value [*Twomey*, 1977] of zero resulted in a reduction of DFDI of 12 Wm^{-2}, still 4 Wm^{-2} more than measured. Use of a phase function based on Mie theory (results not shown) yielded DFDI that differed negligibly (<2 Wm^{-2}) from that obtained with the Henyey-Greenstein phase function used here. Finally, reducing AOT at all wavelengths by the uncertainty in its measurement, 0.01, results in a reduction in DFDI of 5 Wm^{-2}. Simultaneous reduction in SSA, AP, and AOT (550nm) to 0.7, 0.4, and 0.05 respectively can close the gap, but these values are unlikely and/or unrealistic, as outlined above. 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. In contrast, a reduction in AOT (550 nm) by 0.03 (and according to Ångström power law at other wavelengths) brings the model results to within 1 Wm^{-2} of the measured value. As AOT is constrained by the observation of direct-normal Solar irradiance, which the models calculate to high accuracy [*Halthore et al.*, 1997b], reduction beyond the measurement uncertainty needs further justification, as explored below.

Discussion and Conclusions

From Table 1, the uncertainty in the model estimated DFDI δ_{model} due to uncorrelated uncertainties in SSA, AP, AOT and surface reflectance is estimated as 9.3 Wm^{-2}. For the uncertainty in the measurement (75% confidence level) taken as $\delta_{meas} = 5\ Wm^{-2}$, the uncertainty in the difference between modeled and measured DFDI (Figure 1) is 10.6 Wm^{-2}, evaluated as $\delta_{diff} = (\delta^2_{model} + \delta^2_{meas})^{1/2}$. Of the 32 low altitude cases, 20 cases (16 at the 95% confidence level of $\delta_{meas} = 8\ Wm^{-2}$) demonstrate an excess of modeled DFDI over measured.

The gap between the model calculations and measurements can be closed by reducing AOT at all wavelengths and correspondingly increasing atmospheric continuum absorption. In Figure 1, the decrease in AOT, ΔAOT, required to close the gap between modeled DFDI and measured DFDI is also plotted. For each case, the compensating increase in atmospheric absorption was simulated in the model by reducing the TOA Solar irradiance. For BOREAS, closing the gap required reduction in AOT at 550 nm from 0.031 essentially to zero. The wavelength dependence of ΔAOT therefore would be that of the non-Rayleigh extinction measured on that day, which exhibits Ångström exponent of roughly 1; this is consistent with the finding of *Kato et al.* (1997). For all low altitude cases, ΔAOT ranged from about 0.015 to 0.032, with an average, 0.022. The uncertainty in ΔAOT is calculated to be about ±0.014. No trend of ΔAOT is seen with airmass, AOT, or PW. Variation of ΔAOT even within a day suggests that the agent or process responsible for the excess absorption is variable and acts primarily at low altitudes.

A reduction of apparent AOT by ΔAOT of 0.015 to 0.03 (average, 0.022) for the low-altitude cases corresponds to a compensating increase in atmospheric absorptance of 3.4 - 6.8% (average, 5.0%) in the shortwave (here the calculation includes a contribution for the upward flux). The corresponding excess absorption is 23 to 46 Wm^{-2} (average, 34 Wm^{-2}), dayside average, or 12 to 23 Wm^{-2} (average, 17 Wm^{-2}), global average. The excess absorption, determined here for clear skies, is a substantial portion of recently reported excess absorption under cloud-free and possibly cloudy conditions (see *Arking,* [1996] and references therein).

The postulated excess atmospheric absorption compensated by a reduction in aerosol optical thickness, would have important consequences for many areas of atmospheric radiative transfer. For aerosol climatology the excess absorption would masquerade as AOT that has been interpreted in the past as representative of "baseline" or "background" conditions [*Forgan*, 1987]. Examination of some 80,000 measurements of apparent AOT at several widespread locations [*Holben et al.*, 1998], Figure 2, reveals no values below a minimum apparent AOT at 440 nm of 0.025. The lowest reported values may therefore represent optical thickness due to the postulated excess absorption under conditions in which the atmosphere is essentially free of light-interacting aerosols. Such an excess absorptance, 3.4 - 6.8%, would be a substantial increment to the 21% absorptance calculated by MODTRAN for a standard mid-latitude summer atmosphere. For remote sensing, a reduction in apparent AOT of 0.02 - 0.03 would have major consequences for atmospheric correction procedures, as all measurements of AOT to date would need to be reduced, with consequent effects on model-calculated at-sensor radiance. In the absence of an identified absorber or process, the amount of reduction in apparent AOT can be determined at present only by simultaneous measurements of apparent AOT and DFDI under cloud free conditions.

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References

Arking, A., *Science,* Absorption of Solar Energy in the Atmosphere: Discrepancy Between Model and Observations. *273,* 779 - 782, 1996.

A. Berk, L.S. Bernstein, G.P. Anderson, P.K. Acharya, D.C. Robertson, J.H. Chetwynd, and S.M. Adler-Golden, MODTRAN Cloud and Multiple Scattering Upgrades with Applications to AVIRIS, *Remote Sens. Envir., in press,* 1998.

L.S. Bernstein, A. Berk, P.K. Acharya, D.C. Robertson, G.P. Anderson, J.H. Chetwynd, and L.M. Kimball, Very Narrow Band Model Calculations of Atmospheric Fluxes and Cooling Rates, *Journal of Atm. Sci., 53,* 2887 - 2895, 1996.

Betts, A. K. and J. H. Ball, Albedo over the Boreal Forest, *J. Geophys. Res., 102,* 28,901 - 28,909, 1997.

Forgan, B. W., Aerosol optical depth, *Baseline (CSIRO) Atmospheric Program (Australia) 1985,* p. 56, 1987.

Halthore, R. N., S. Nemesure, S. E. Schwartz, D. Imre, G. Anderson, J. J. Michalsky, and M. H. Bergin, Comparison of model estimated and measured total surface irradiance under cloud-free conditions - A closure experiment (abstract), *Eos Trans. AGU, 78,* Fall Meet. Suppl., F108, 1997a.

Halthore, R. N., S. E. Schwartz, J. J. Michalsky, G. P. Anderson, R. A. Ferrare, B. N. Holben, H. Ten Brink. Comparison of model estimated and measured direct-normal solar irradiance, *J. Geophys. Res., 102,* 29,991 - 20,002, 1997b.

Halthore, R. N., T. F. Eck, B. N. Holben, and B. L. Markham, Sun photometric measurements of atmospheric water vapor column abundance in the 940-nm band, *J. Geophys. Res., 102,* 4343 - 4352, 1997c.

J. M. Haywood and K. P. Shine, The effect of anthropogenic sulfate and soot aerosol on clear sky planetary radiation budget, *Geophys. Res. Lett., 22,* 603 - 606, 1995.

Holben, B. N., T. F. Eck, I. Slutsker, D. Tanre, J. P. Buis, A. Setzer, E. Vermote, J. A. Reagan, Y. J. Kaufman, T. Nakajima, F. Lavenu, I. Jankowiak and A. Smirnov, AERONET-A Federated Instrument Network and Data Archive for Aerosol Characerization, *Remote Sens. Envir., submitted,* 1998.

Kato, S., T. P. Ackerman, E. E. Clothiaux, J. H. Mather, G. G. Mace, M. L. Wesely, F. Murcray, and J. Michalsky. Uncertainties in modeled and measured clear-sky surface shortwave irradiances, *J. Geophys. Res., 102,* 25,881 - 25,898, 1997.

Lacis, A.A., J. Chowdhary, M.I. Mishchenko, and B. Cairns, Modeling errors in diffuse-sky radiation: vector vs. scalar treatment, *Geophys. Res. Lett., 25,* 135 - 138, 1998.

Marshall, S. F., D. S. Covert and R. J. Charlson, Relationship between asymmetry parameter and hemispheric backscatter ratio: implications for climate forcing by aerosols, *Appl. Optics, 34,* 6306 - 6311, 1995.

Shewchuk, S. R., Surface mesonet for BOREAS, *J. Geophys. Res., 102,* 29,077 - 29,082, 1997.

Twomey, S. *Atmospheric Aerosols,* 302 pp., Elsevier, 1977.

Vermote, E. F., D. Tanre, J. L. Deuze, M. Herman and J. J. Morcrette, *IEEE Trans. Geosci. Remote Sens., 35,* 3 - 15, 1997

Walter-Shea, E. A., B. L. Blad, C. J. Hays, M. A. Mesarch, D. W. Deering and E. M. Middleton, Biophysical Properties Affecting Vegetative Canopy Reflectance and Absorbed Photosynthetically Active Radiation at the FIFE Site, *J. Geophys. Res., 97,* 18,925 - 18934, 1992.

Wang, J., G.P. Anderson, H.E. Revercomb, R.O. Knuteson, Validation of FASCOD3 and MODTRAN3: Comparison of Model Calculations with Ground-Based and Airborne Interferometer Observations Under Clear-Sky Conditions, *Appl. Optics, 35,* 6028-6040, 1996.

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