Diffuse Shortwave Irradiance at Surface - Further Issues and Implications

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Introduction

Recent studies (Halthore et al. 1998; Kato et al. 1997; Halthore et al. 1997) indicate that radiative transfer models accurately compute the direct-normal solar irradiance (DNSI) at the surface while overestimating the diffuse downward irradiance (DFDI) in cloud-free skies. This can only mean that for realistic aerosol scattering and known instrumental bias errors, some atmospheric absorption process was unaccounted for in the models that compute irradiance components and those that estimate the aerosol optical thickness (AOT) from sunphotometer measurements. The amount of model overestimation is proportional to the magnitude of missing absorption in the models and is shown to be 3% to 8% absorptance, which is 15% to 40% in excess of that present in models. This is substantial excess. It is, however, a point of current dispute arising mainly from a disagreement regarding accuracy in DFDI measurements. At high altitudes, models correctly compute DFDI measured using instruments of similar construction with identical calibration protocols. We show here that the conclusion of excess atmospheric absorption reached in previous studies is substantially correct and the methods employed to account for instrumental artifacts are reliable.

Pyranometry

Pyranometers measure total downward shortwave (SW) irradiance by exposing a horizontal thermopile detector to the hemispherical sky. The detector is enclosed in a double-walled glass dome that provides wavelength selectivity and helps keep the detector free of dust. Ventilation is used in the pyranometers to provide control over convective and conductive heat losses and to prevent condensation over the glass dome. Obstructing the sun's disc by a metal ball (or a shadowband), enables measurement of DFDI after correcting for a slight amount of diffuse light obstructed by the shadow device. The direct-normal component of the irradiance is given by the difference between the total and diffuse irradiance divided by the cosine of the solar zenith angle. A plot of diffuse irradiance measured by two pyranometers shows (Figure 1) that the uncorrected signal is negative during night when the SW irradiance is zero.

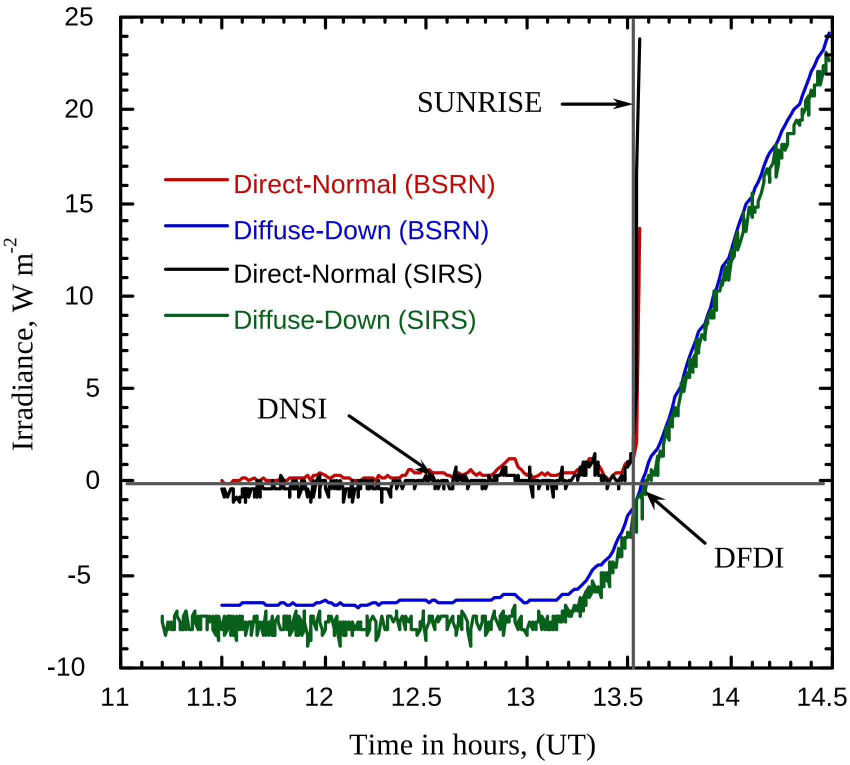

Figure 1. On a cloud-free day (December 10, 1996) at Southern Great Plains (SGP) site, pyrheliometer-measured DNSI and pyranometer-measured DFDI obtained by two groups of instruments—Baseline Surface Radiation Network (BSRN) (smooth lines, 1 min. average of 1 s data) and Solar Infrared Station (SIRS) (noisier lines, instantaneous values every 20 s) show that a sunrise, indicated by a steep rise in DNSI, DFDI is negative when it clearly ought to be positive.

Also plotted in the same figure, are two traces of DNSI as measured by two pyrheliometers, which measure DNSI using a thermopile detector with a narrow field-of-view (~5°) collimator. Clearly, at the time of sunrise indicated by a sharp increase in the pyrheliometer signal DFDI traces in both the instruments are negative. This is contrary to the common observation that diffuse skylight precedes sunrise by about 15 minutes and therefore, the DFDI traces ought to be positive. Negative values in DFDI traces therefore constitute real signal. What causes negative offsets?

Origin of the Negative Offset and its Compensation

The values at night are negative because of the inherent weakness in the calibration procedure adopted for all pyranometers. In the sunshade technique (Forgan 1996), DNSI determined by shading and unshading the pyranometer is compared to that measured by an active cavity radiometer (ACR), whose accuracy is ~0.3%. For horizontal downward irradiance E, let the voltage response V of an ideal pyranometer with perfect cosine response be expressed as,

$$V = R' E + V_0', \tag{1}$$

where R' is the calibration coefficient in $V/(W\ m^{-2})$ and V_0' is the offset voltage comprising of three components: (a) an electrical component unrelated to electromagnetic radiation or to heat balance, (b) a component due to instrument cooling that is SW independent, and (c) a component due to instrument cooling that is SW dependent. Thus,

$$V_0' = V_0 + \alpha\ E, \tag{2}$$

where V_0 represents the SW independent portions (a) and (b) and (α E) represents the SW dependent portion (c). In general, both terms on the right hand side depend on factors that affect cooling, specifically longwave (LW) cooling. Substituting for V_0' in Eq. (1), we get

$$V = (R' + \alpha)\ E + V_0 = R\ E + V_0. \tag{3}$$

Here $R = R' + \alpha$. If V_{sh} and V_{us} are the voltages measured in the shaded and unshaded mode respectively, then,

$$R = (V_{us} - V_s) / (E_{us} - E_s) = (V_{us} - V_s) / (E_{dir} \operatorname{Cos} \theta). \tag{4}$$

Direct irradiance, E_{dir}, is measured by an ACR. Thus, determination of R by calibration includes the SW effect on cooling to first order. For non-ideal pyranometers, R must be determined at various solar zenith angles and the procedure, performed for instruments used here, is quite tedious. The zero offset, about which no information is obtained by this calibration technique, is determined by measuring the voltage for zero SW irradiance, that is at night, and scaling it appropriately for LW emission to the atmosphere using as surrogate the net LW irradiance as measured by a pyrgeometer (Figures 2a and 2b). One could suppress the nighttime negative offset by compensating circuitry without the fear of jeopardizing daytime measurements, since daytime and nighttime offsets should be comparable to within a few watts of each other.

DFDI measurements, when compensated for negative offsets as described herein, do not depict the "Rayleigh problem" in which measured DFDI appears (Cess et al. 1999) to be less than that computed for a Rayleigh atmosphere.

Results

Data spans a period from 1994 to present and was obtained at four sites: two high altitude and two low altitude. Results show that radiative transfer models employing the current knowledge of gaseous transmission and sunphotometer inferred aerosol extinction and using different multiple scattering schemes, consistently overestimate DFDI at all low altitude sites, while correctly estimating DNSI. To within estimated uncertainties models correctly estimate measured DFDI at two high altitude sites (Figure 3). A sensitivity analysis shows (Figure 4) that at low AOT, (~0.06 at 550 nm) highly unusual aerosol scattering properties are required to close the gap between models and measurements. At high AOT (~0.2 at 550 nm), the overestimate is not sensitive to aerosol scattering properties.

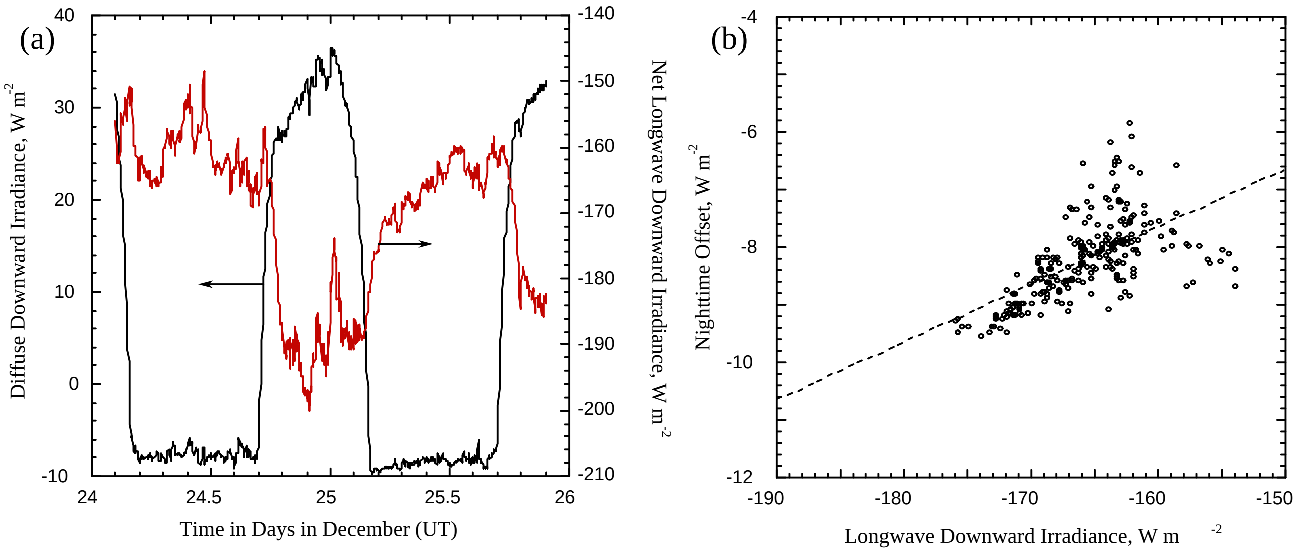

Figure 2. In (a) DFDI as measured by a shaded pyranometer is plotted against time of day as fractional days universal time (UT) in December at Mauna Loa (MLO, altitude: 3,400 m). Net LW surface irradiance, as measured by an uplooking pyrgeometer, is also plotted in this figure. The apparent weak correlation between DFDI and LW flux seen in (a) is confirmed in (b) where the two are plotted against each other ($R^2 = 0.4$). Using the LW flux as a surrogate, the relationship obtained in (b) helps estimate the daytime offset values.

Discussion

As molecular scattering is well represented in the models, for realistic aerosol scattering properties, it is concluded that the model overestimate is due to an overestimate in the AOT. However, since the extinction is accurately measured by sunphotometers (DNSI closure), it follows that an atmospheric absorbing component is wrongly attributed to AOT. The required reduction in AOT, compensated by an increase in atmospheric absorption, is able to close the gap between models and measurements. On average, the excess absorption contributes a vertical optical thickness of 0.022 at 550nm and appears to be a continuum, since it would have otherwise been easily detected. This translates to an excess absorptance of 5% ± 3%. The uncertainty arises from the uncertainty in extinction measurements (using sunphotometers) and the variability among the many cases seen in Figure 3.

Other Pertinent Measurements

Figure 5 shows that model calculations of sky radiance (with measured inputs) exceed that measured with a narrow field-of-view radiometer. Better agreement is possible when the apparent AOT is reduced in the models. Figure 6 shows the existence of a gap in apparent AOT of about 0.022 indicating the presence of an atmospheric absorber whose extinction has been wrongly attributed to AOT.

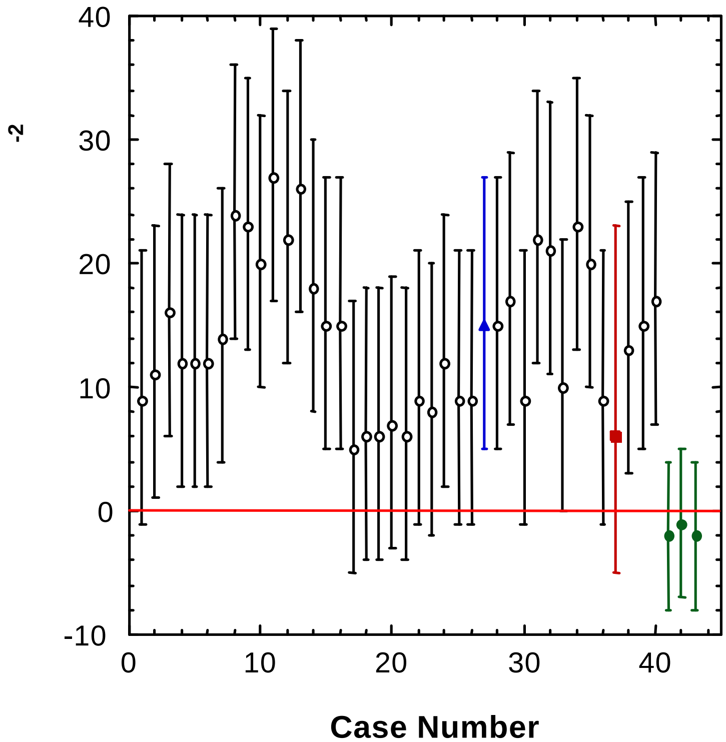

Figure 3. Model overestimates measured DFDI for all low altitude cases 1 to 40 (open circles, filled triangle, and filled square). At high altitudes (filled circles) models correctly estimate measured DFDI to within the uncertainties (± 6 W m^{-2}) in measurements and model inputs. Seventy-five percent confidence limits are shown for "low" AOT case (filled triangle, case 27), "high" AOT case (filled square) and all other low altitude cases. 27 cases out of 40 low altitude cases show a clear model overestimate.

What is Causing the Excess Absorption?

It appears that the gases that have been investigated (H_2O monomers, dimers, and collision pairs involving H_2O and O_2, N_2), cannot account for the 5% excess absorptance (0.02 in vertical optical thickness 550 nm and increasing toward lower wavelengths). An alternative source of this excess absorption might be small, highly absorbing particles (imaginary index of refraction ~0.4 to 1.0 corresponding to soot, for example) of size ~0.01 µm to 0.05 µm, which absorb more light than they scatter. Our calculations show that ubiquitous continental presence of such particles in reasonable quantity in the boundary layer could explain the required continuum absorption.

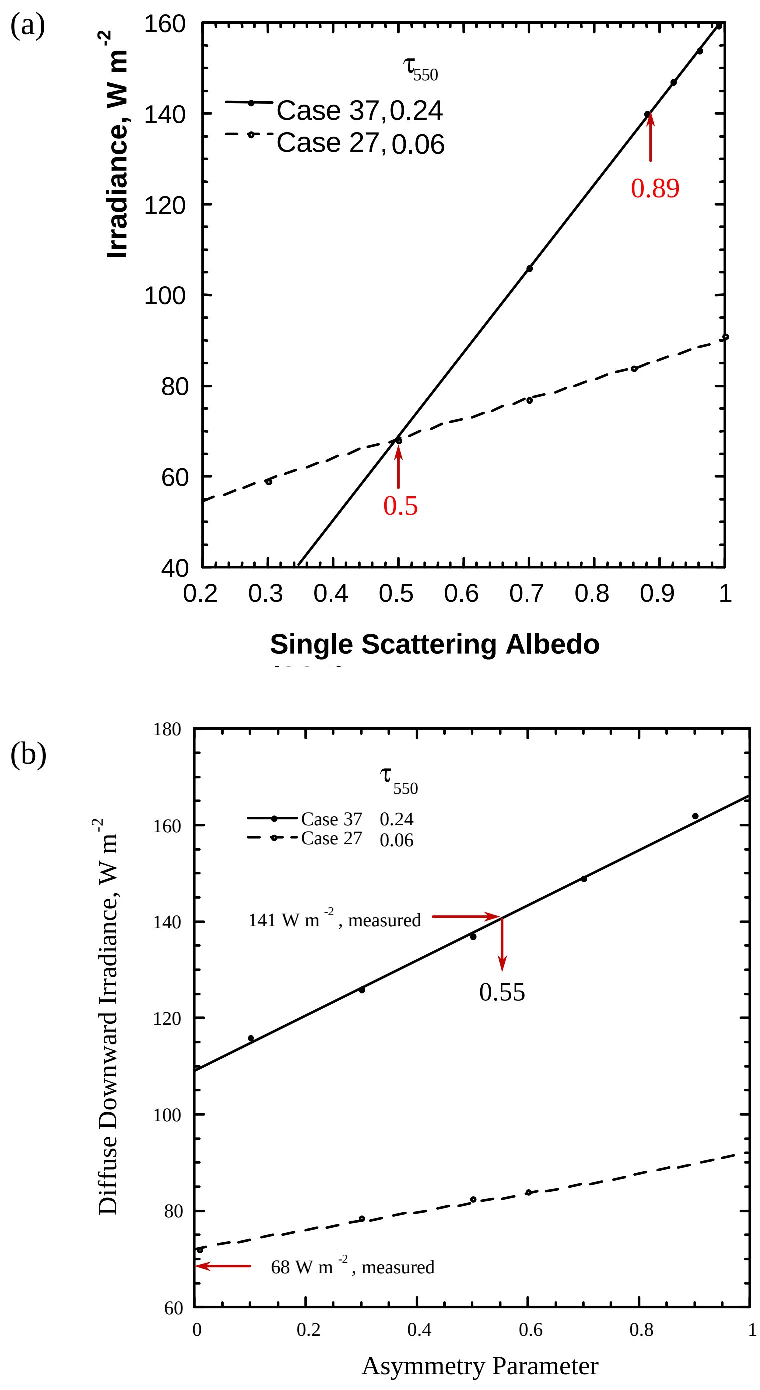

Figure 4. DFDI sensitivity to single-scattering albedo ([SSA] figure on left) and asymmetry parameter (AP) are plotted for a low AOT case (τ_{550} = 0.06, September 27, 1997; case 27, open circles) and a high AOT case (τ_{550} = 0.24, October 4, 1997; case 37, filled circles). Arrows and numbers below represent values of SSA or AP that will reproduce measured DFDI. No physically plausible value of AP can bring the modeled value down to a measured value of 68 W m^{-2} for the low AOT case.

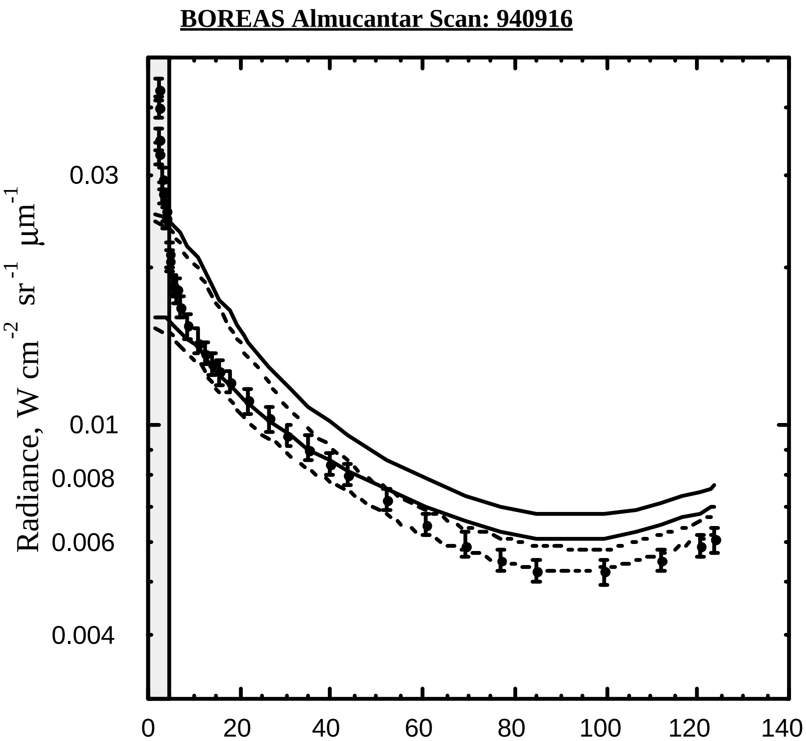

Figure 5. Sky radiance along the almucantar (i.e., at constant solar zenith angle but many azimuth angles) measured at 440 nm by a calibrated Cimel Radiometer (solid filled circles with ±5% uncertainty) is plotted against scattering angle and compared with Moderate Resolution Transmittance model (MODTRAN) 3.5 8-stream (solid lines) and 2-stream (dashed lines) models. Upper curves are for uncorrected AOT as inferred from the same instrument in the sunphotometer mode of operation. Lower curves, which are better fits to data, are obtained by reducing AOT by 0.025 at 440 nm. Values near zero degree are contaminated by direct solar radiance. Note that the detection scheme used here (silicon detectors in photovoltaic mode) is not influenced by offsets, as is the case with the diffuse/direct irradiance ratio comparison with the MFRSR (Kato et al. 1997).

Conclusions

The observation that models overestimate DFDI in cloud-free sky at low elevation sites but not at high altitudes, indicates that measurement errors are well understood and it is the models that do not account for an atmospheric absorbing process. This absorption is most likely due to very small absorbing particles present in the boundary layer. Measurements of direct and diffuse surface irradiance at the Atmospheric Radiation Measurement (ARM) site are accurate provided appropriate corrections as outlined here are made for the offsets.

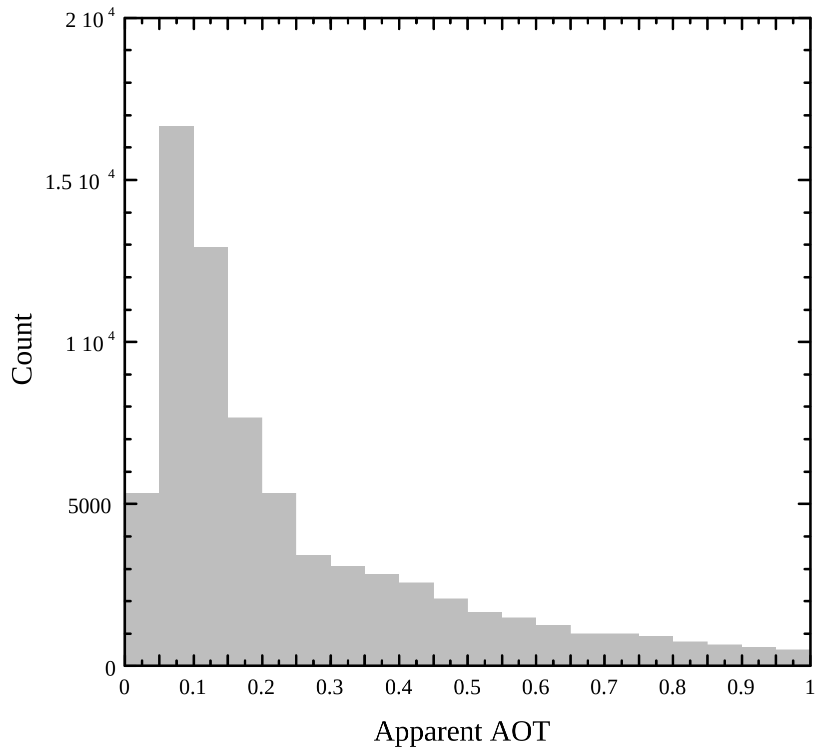

Figure 6. Histogram of 80,000 values of AOT at 440 nm inferred from sunphotometer measurements at five locations around the world reveals that values below 0.03 are extremely rare; there are no values below 0.02. About 10,000 measurements in the Eastern United States; 12,000 in Brasilia, Brazil; and 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 is obtained from calibrated sunphotometers (accuracy 0.01 at airmass of 1) belonging to AERONET (Holben et al. 1998).

Acknowledgments

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