

Prediction and Measurement of Direct-Normal Solar Irradiance: A Closure Experiment

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Abstract

Direct-normal solar irradiance (DNSI), the total energy in the solar spectrum incident on a plane perpendicular to the Sun's direction on a unit area at the earth's surface in unit time, depends only on the atmospheric extinction of sunlight without regard to the details of extinction - whether absorption or scattering. Here we describe a set of closure experiments performed in north-central Oklahoma, wherein measured atmospheric composition is input to a radiative transfer model, MODTRAN-3, to predict DNSI, which is then compared to measured values. Thirty-six independent comparisons are presented; the agreement between predicted and measured values falls within the combined uncertainties in the prediction (2%) and measurement (0.2%) albeit with a slight bias (~1% overprediction) that is independent of the solar zenith angle. Thus these results establish the adequacy of current knowledge of the solar spectrum and atmospheric extinction as embodied in MODTRAN-3 for use in climate models. An important consequence is the overwhelming likelihood that the atmospheric clear-sky absorption is accurately described to within comparable uncertainties.

Introduction

Here we perform a simple yet robust closure experiment. We examine the ability of a moderate resolution (2 cm⁻¹) radiative

transfer model (MODTRAN-3 v1.3, Anderson et al. 1995) to accurately estimate DNSI in comparison with accurate measurements at the Southern Great Plains (SGP) Cloud and Radiation Testbed (CART) site in Oklahoma. We choose only clear days in April 1996 to avoid complications arising from the presence of clouds.

E, DNSI, needs as input the extraterrestrial spectral solar irradiance (referred to the mean Sun-Earth distance) $E_0(\lambda)$, in addition to spectral transmittance of the atmosphere $T(\lambda, \mu_0)$, along the slant path to the top of the atmosphere (solar zenith angle θ_0) at the time of measurement. Thus,

$$E = \left(\frac{1}{R^2} \right) \int E_0(\lambda) T(\lambda, \mu_0) d\lambda \quad (1)$$

where integration is performed over the solar spectrum, R (in Astronomical Units, A.U.; mean Sun-Earth distance = 1 A.U.) is the Sun-Earth distance at the time of measurement, and the transmittance $T(\lambda)$ is given by Bouguer's law,

$$\begin{aligned} T(\lambda, \mu_0) &= T_{\text{Rayleigh}}(\lambda, \mu_0) T_{\text{gas}}(\lambda, \mu_0) T_{\text{aerosol}}(\lambda, \mu_0), \\ &= \exp - \left(m \tau_{\text{Rayleigh}}^\lambda + m \tau_{\text{gas}}^\lambda + m \tau_{\text{aerosol}}^\lambda \right) \end{aligned} \quad (2)$$

where m is the airmass along slant path, defined in the absence of refractive effects as $m = 1 / \mu_0 = 1 / \cos \theta_0$, and each τ_i denotes a contribution to vertical optical thickness

due to the indicated atmospheric component. The three major components that cause attenuation of sunlight are 1) Rayleigh or molecular scattering; 2) gaseous absorption due to ozone, oxygen, water vapor, nitrogen (continuum), carbon-dioxide and other gases; and 3) absorption and scattering by aerosols. The error in the calculated DNSI arises from the error in the solar spectrum as represented in the model and the error in the estimate of the atmospheric transmittance, under the assumption that the Sun-Earth distance and the airmass are accurately known.

MODTRAN-3 Evaluation and Sensitivity to Inputs

MODTRAN-3 is evaluated against a line-by-line code that uses the latest molecular data base, HITRAN-96 (Rothman et al. 1977). The comparison shows that the percentage difference between the two models in many of the molecular absorption bands is within 3%, and in a few cases, it is as much as 10%. The impact of this error on the DNSI integrated over the entire solar spectrum is, however, negligible. The combined effect of error in all the bands has an impact on the DNSI of about 0.3%, which for extra-terrestrial solar irradiance of 1368 W m^{-2} corresponds to about 4 W m^{-2} . Thus the band model parameterizations in MODTRAN-3 of the important molecular absorption bands are adequate and lead to an estimate of DNSI that is consistent with an estimate of a more accurate line-by-line radiative transfer code.

Examination of the sensitivity of DNSI to atmospheric variables of aerosol optical thickness (AOT), precipitable water (PW), Ångström exponent, ozone column abundance and a combination of AOT and PW shows that the largest change in DNSI is due to uncertainty in AOT followed by uncertainty in PW measurement. (Uncertainties used in this analysis reflect the ability to estimate the above quantities either by direct measurement or by inference from climatology.) The reason for this sensitivity to AOT is because aerosol attenuation is present in the entire solar spectrum as opposed to discrete absorption in the molecular absorption bands. Therefore it is important that AOT be accurately specified as input to MODTRAN-3.

At the CART site, the measurement of AOT is accomplished by two types of instruments: narrow field-of-view (1.2°) sun photometer, which measures direct irradiance in several spectral bands, and horizontally placed shadow-band radiometers, which measure the hemispherical downward total and diffuse-sky irradiance, again in several spectral bands, from which DNSI is obtained as a difference between total and diffuse divided by the cosine of the solar zenith angle.

Results show that for the period of measurements the two instruments yield AOT in comparable channels to within the individual uncertainties of each instrument (0.01 for the Cimel sun photometer and 0.02 for the multifilter rotating shadowband radiometer [MFRSR]). Small systematic differences are found and are explained in Halthore et al. (1997). Precipitable water inferred from radiosonde measurements in April is checked by sun photometer measurements to be within their stated uncertainty ($\pm 10\%$), and use of ozone from climatology (available in MODTRAN-3 itself) is checked to be within about 20% of the satellite measurements.

The model estimate of DNSI needs small corrections because of finite wavelength range ($<5 \text{ nm} - 0.45\%$) and the use of slightly higher solar constant than the standard value of 1366 W/m^2 (0.52%). These two corrections are opposite to each other; the net effect is the decrease of about 0.07% from the model estimated value. DNSI measurement is made by a normal incidence pyrhelometer (NIP) itself calibrated with respect to an absolute cavity radiometer (ACR). The stated uncertainty in DNSI measurement estimated by comparison with world standards is 0.2%. However, because of the finite field of the view of both these instruments (5.7 and 5 respectively), a correction is necessary to exclude circumsolar radiation from the DNSI. This effect is about 0.4%.

Results and Discussion

Thirty-six cases were identified as yielding instantaneous measurements of DNSI contemporaneously with radiosonde launches. Estimated and measured irradiance are plotted for comparison in Figure 1 with all the corrections, described previously, applied. No averaging is performed. Cases exhibiting low values of irradiance result from measurements at high solar zenith angles. Although the correlation between the model estimates and measurements is excellent with an R^2 of 0.997 (Figure 2), for the 36 measurements on average the model slightly overestimates measured DNSI by $(0.72 \pm 0.81)\%$; for an average DNSI of 839 W m^{-2} , this corresponds to $6.0 \pm 6.8 \text{ W m}^{-2}$ (1 standard deviation).

To explore the possibility of insufficient accounting for the atmospheric attenuation including absorption in the model, dependence of the percent difference between model estimated and measured DNSI on the airmass is examined (Figure 2). The data show more scatter at low airmass than at airmass above 1.7. At airmass greater than 1.7, the percent difference appears almost constant at about 1.0% with a slight increasing trend, which is barely observable when compared with the variability in the ordinate values. A linear fit for 20 data points in the airmass range 1.7 to 3.3 (Figure 2)

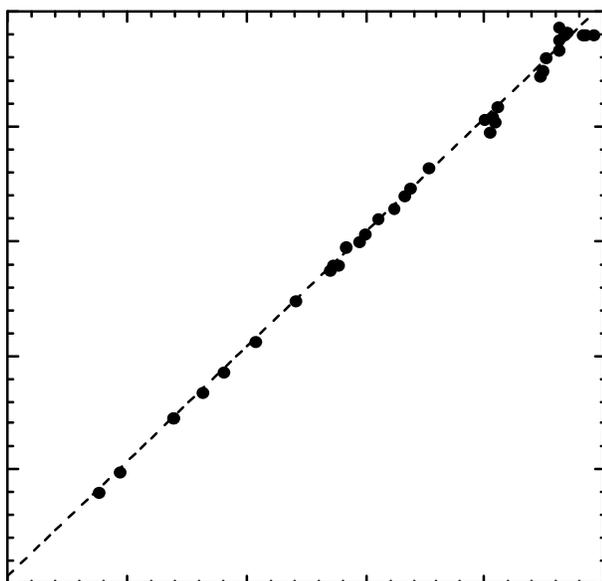


Figure 1. MODTRAN-3 estimated DNSI is plotted against NIP measured values; curve fit is shown by the dashed line. The 1:1 line (solid) is shown for comparison. The variation in DNSI is due mainly to variation in solar zenith angle. The correlation exhibits a bias. ($R^2=0.997$). The linear fit to the data yields a slope of 0.9949 and an offset of 10.273 W m^{-2} .

yields a slope $(0.05 \pm 0.10) \% \text{ airmass}^{-1}$. Since absorption by a gaseous species that is not represented or under-represented in the model would be manifested in such a plot as a linear increase in percent error with increasing airmass (for small percent errors or small air masses), the maximum unaccounted for attenuation (including absorption) is 0.15% (slope plus standard error). A similar exercise with percent difference plotted against path abundance of water yields a slightly decreasing slope with path water in cm to yield $(-0.000523 \pm 0.0011 \text{ percent per cm}_{\text{H}_2\text{O}})$ for a maximum unaccounted for attenuation due to water of $0.0006\% \text{ cm}^{-1}$.

The variability in the percent difference between measured and model estimated DNSI is greater at low airmass than at high airmass (Figure 2). This is due to uncorrelated fluctuations in NIP measured DNSI, which is instantaneous, and Cimel sun photometer measured AOT, which is an average of 3 measurements taken 30 s apart. The maximum unaccounted for attenuation in MODTRAN-3 (including absorption) seen here is 0.15% (slope plus standard error).

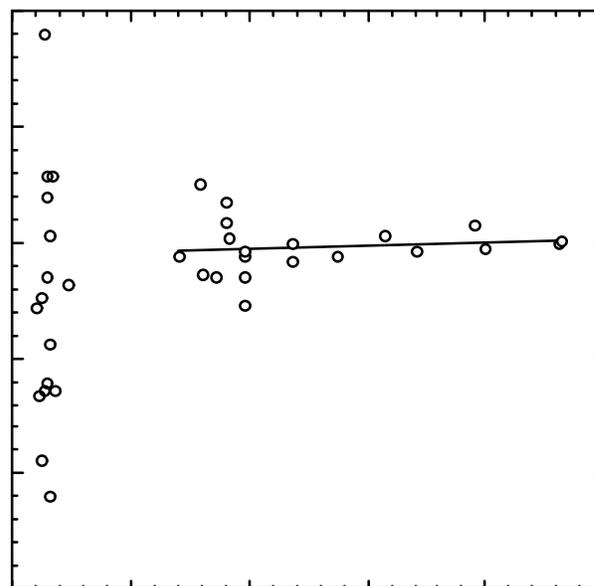


Figure 2. Percent difference, $(\text{DNSI}_{\text{model}} - \text{DNSI}_{\text{meas}})/\text{DNSI}_{\text{meas}}$, between the model estimated and measured DNSI is plotted as a function of airmass to examine the effect of increasing column abundance of attenuators, especially gases. The spread in ordinate values at low airmass is most likely due to atmospheric non-uniformity and atmospheric radiance effects in the FOV (see text). At large airmass the percent difference manifests as a bias that is almost independent of airmass as shown by the linear fit for points whose airmass is greater than 1.7.

This corresponds to a vertical optical thickness of 0.0015 that is unaccounted for. In contrast Arking (1996) found a discrepancy of 50 Wm^{-2} in dayside average flux between a GCM and a global irradiance data set. If the total upward and downward flux through the lower part of the atmosphere were assumed as approximately equal to 1000 Wm^{-2} , the percent discrepancy between model and measurement seen by Arking is 5% at airmass of 2, which translates to a vertical optical thickness of the unknown absorber to be 0.025, much higher than what is found here. If MODTRAN-3 suffered the same inadequacies in parameterization, the resulting effect on DNSI would be readily apparent as a bias that would increase with increasing airmass (slope $\sim 2.5\% \text{ airmass}^{-1}$) or water path abundance. Thus the MODTRAN-3 calculation of DNSI, and by extension its treatment of atmospheric absorption, does not exhibit the underestimated absorption that Arking ascribed to general circulation models (GCMs).

Conclusions

Comparison of the measured and model estimated DNSI constitutes a simple yet robust closure experiment. A medium resolution radiative transfer program, MODTRAN-3, which uses band models for atmospheric absorption that represent current knowledge of absorption by atmospheric gases in the solar spectrum, together with measured values of AOT, water vapor and ozone, was used to estimate DNSI and compare it with accurately measured values. For 36 independent measurements, the model slightly overestimated the measured DNSI by $(0.72 \pm 0.81)\%$ (one standard deviation). The data base on which MODTRAN-3 band model parameters are based is therefore suitable for incorporation into global, climate and weather models. Using analysis of the dependence of the percent difference between the model estimated and measured DNSI on airmass and path abundance of water vapor, it is shown here that the bias is not due to under representation of clear sky atmospheric absorption, but rather is due to an unknown *combination* of factors that may include the solar constant used in the model, aureole brightness in the measurements, solar energy at wavelengths beyond $5 \mu\text{m}$ in the model estimate, and uncertainty in the AOT measurement.

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