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PREDICTION AND MEASUREMENT OF DIRECT-NORMAL SOLAR IRRADIANCE: A CLOSURE EXPERIMENT

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DISCLAIMER

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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 an 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 direct-normal solar irradiance (DNSI) in comparison with accurate measurements at the Southern Great Plains (SGP) 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,

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

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,

$$\begin{aligned} T(\lambda,\mu_0) &= T_{\text{Rayleigh}}(\lambda,\mu_0)T_{\text{gas}}(\lambda,\mu_0)T_{\text{aerosol}}(\lambda,\mu_0), \\ &= \exp-(m\tau^{\lambda}_{\text{Rayleigh}} + m\tau^{\lambda}_{\text{gas}} + m\tau^{\lambda}_{\text{aerosol}}), \end{aligned} \tag{2}$$

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 Rayleigh or molecular scattering, gaseous absorption due to ozone, oxygen, water vapor, nitrogen (continuum), carbon-dioxide and other gases, and 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 which 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 extraterrestrial 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 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 Cimel sun photometer and 0.02 for 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 (± 10%) and use of ozone from climatology (available in MODTRAN-3 itself) is checked to be within about 20% of the satellite measurements.

Model estimate of DNSI needs small corrections because of finite wavelength range (<5 mm - 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 NIP itself calibrated with respect to 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

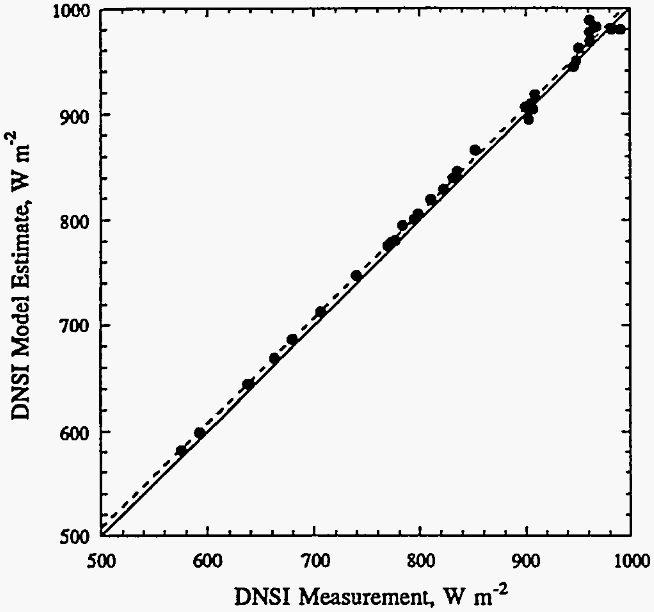

Figure 1. MODTRAN-3 estimated DNSI is plotted against NIP measured values; curve fit is shown by the dashed line. The 1:1 line (solid) is shown for comparison. The variation in DNSI is due mainly to variation in solar zenith angle. The correlation exhibits a bias. (R^2=0.997). The linear fit to the data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

excellent with an R^2 of 0.997 (Figure 6), for the 36 measurements on average the model slightly overestimates measured DNSI by (0.72 ± 0.81)%; for an average DNSI of 839 W m^{-2} this corresponds to 6.0 ± 6.8 W m^{-2} (1 standard deviation).

In order 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

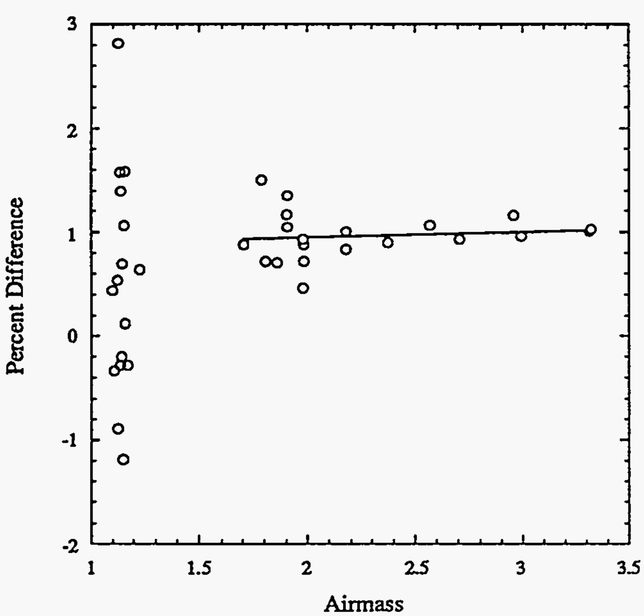

Figure 2. Percent difference, $(DNSI_{model} - DNSI_{meas})/DNSI_{meas}$, between the model estimated and measured DNSI is plotted as a function of airmass to examine the effect of increasing column abundance of attenuators, especially gases. The spread in ordinate values at low airmass is most likely 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.

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) yields a slope (0.05 ± 0.10)% 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 airmasses), 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 ± 0.0011 percent per cm_{H_2O}) for a maximum unaccounted for attenuation due to water of 0.0006% 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). This corresponds to a vertical optical thickness of 0.0015 that is unaccounted for. In contrast Arking (1996) found a discrepancy of 50 W m^{-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 W m^{-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 ~2.5% 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 GCMs.

Conclusions

Comparison of the measured and model estimated direct normal solar irradiance (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 estimate DNSI. and compare it with accurately measured values. For 36 independent measurements the model slightly overestimated the measured DNSI by (0.72 ± 0.81)% (one standard deviation). The data base on which MODTRAN-3 band model parameters are based is therefore suitable for incorporation into global and climate and weather models. 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 μm in the model estimate, and uncertainty in the AOT measurement.

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