Toward Improved Modeling of Spectral Solar Irradiance for Solar Energy Applications

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TOWARD IMPROVED MODELING OF SPECTRAL SOLAR IRRADIANCE FOR SOLAR ENERGY APPLICATIONS

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ABSTRACT: This study introduces the National Renewable Energy Laboratory's (NREL's) recent efforts to extend the capability of the Fast All-sky Radiation Model for Solar applications (FARMS) by computing spectral solar irradiances over both horizontal and inclined surfaces. A new model is developed by computing the optical thickness of the atmosphere using a spectral irradiance model for clear-sky conditions, SMARTS2. A comprehensive lookup table (LUT) of cloud bidirectional transmittance distribution functions (BTDFs) is precomputed for 2002 wavelength bands using an atmospheric radiative transfer model, libRadtran. The solar radiation transmitted through the atmosphere is given by considering all possible paths of photon transmission and the relevent scattering and absorption attenuation. Our results indicate that this new model has an accuracy that is similar to that of state-of-the-art radiative transfer models, but it is significantly more efficient.

Keywords: Solar Radiation, Optical Properties, PV System

1 INTRODUCTION

Radiative transfer models play a crucial role in assessing and forecasting solar resources for electricity conversion. NREL developed FARMS [1] to acccurately and efficiently evaluate broadband solar irradiances for all-sky conditions over horizontal surfaces; however, the demands of solar energy research often exceed the capabilities of FARMS as well as other conventional radiative transfer models. For example, solar irradiances in numerous narrow-wavelength bands are not provided by FARMS, but they are particluarly useful in solar cell research because of the spectral response of photovoltaic (PV) panels. Further, solar energy studies require solar irradiances over inclined surfaces because solar systems track the sun on multiple axes. Although numerous solar irradiance models can compute spectral or broadband solar irradiances over inclined surfaces, they are either designed for clear-sky conditions or use empirical models to simulate plane-of-array (POA) irradainces [2-4]. The purpose of this study is to extend the capability of FARMS by developing an all-sky model to efficiently provide physical solutions of spectral solar irradiances over both horizontal and inclined surfaces.

2 CLOUD BIDIRECTIONAL TRANSMITTANCE DISTRIBUTION FUNCTION

To develop a new irradiance model capable of rapidly simulating spectral irradiance on inclined surfaces, cloud bidirectional transmittance distribution functions (BTDFs) need to be combined with clear-sky absorption and scattering [5, 6]. Cloud BTDFs are functions of wavelength, cloud thermodynamic phase, solar zenith angle, viewing zenith angle, relative azimuth angle, cloud optical thickness, and effective particle size. Because the computation of BTDFs by libRadtran [7] is time-consuming, it is important to determine the appropriate spectral and spatial resolutions. Figure 1a compares the spectral resolutions of different radiative transfer models and BTDF databases. A clear-sky radiative transfer model, SMARTS2 [2], uses 2,002 wavelengths from 0.28–4.0 μm according to the absorbing lines of trace gases in the atmosphere. Another spectral radiative transfer model, TMYSpec [3], considers wavelengths for every 10 nm from 0.3–1.8 μm; however, cloud BTDF is sensitive to wavelength because of the variation in the refractive indexes for water droplets and ice crystals. Thus, fewer wavelengths can be used to compute cloud BTDFs to save computing time. We investigated BTDFs of water and ice clouds and found that 97 wavelengths (red dots in Fig.1a) from 0.2–4.0 μm provided the best balance between computing time and accuracy. The BTDF can be interpolated to 2,002 wavelengths and combined with SMARTS2 to compute all-sky spectral radiances.

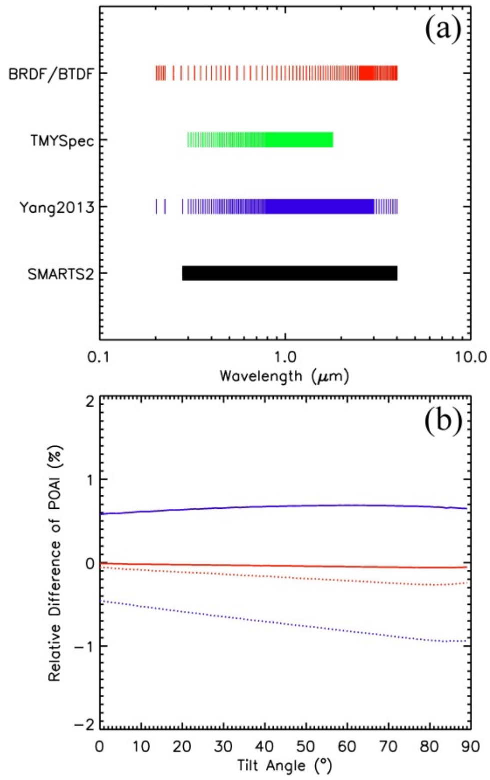

Figure 1: (a) Comparison of spectral resolutions; (b)

POA irradiances computed from 50 viewing zenith angles and 36 relative azimuth angles (solid lines) and those from 25 viewing zenith angles and 18 relative azimuth angles (dashed lines) for water (red) and ice (blue) clouds.

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To determine the resolution of viewing angles in the new radiative transfer model, we used libRadtran to compute cloudy-sky radiances of water and ice clouds for optical depth τ=5, effective particle size De=10 µm, solar zenith angle of 30º, and wavelength λ=0.6 µm. One hundred viewing zenith angles and 180 relative azimuth angles (for every 1º) were used in the computation. To save computing time, fewer viewing zenith angles and relative azimuth angles were also tested. Figure 1b compares the relative error of the POA irradiances from using 50 viewing zenith angles and 36 relative azimuth angles (solid lines) and 25 viewing zenith angles and 18 relative azimuth angles (dashed lines). POA irradiances from 100 viewing zenith angles and 180 relative azimuth angles were used as the ground truth. Compared to the solid lines in Fig.1b, 25 viewing zenith angles and 18 relative azimuth angles give less than 1% uncertainties.

2 FARMS WITH NARROWBAND IRRADIANCES OVER TILTED SURFACES (FARMS-NIT)

To compute the solar radiation transmitted through a cloudy atmosphere, we divide the atmosphere into three layers: a cloud/aerosol layer and the clear-sky layers above and below the cloud layer. For the clear-sky layers, the optical thicknesses in 2,002 wavelength bands are computed by a clear-sky model, SMARTS2 [2]. In each layer, a photon can either directly transmit through the layer or be scattered by air molecules or cloud particles. To derive surface radiation, we consider all possible photon paths that are listed in Table 1, where "D" denotes direct transmission and "S" denotes scattering within the layer. From Path 7, the direct solar radiation can be easily computed from the Beer-Bouguer-Lamber law [8] and the optical thicknesses of the clouds and the atmosphere. Following the Rayleigh scattering correction technique and [9], Rayleigh scattering is considered only once in the whole atmosphere. Thus, paths 1–4 and 6 are used in the computation of diffuse solar radiation. By solving the radiative transfer equation with a single-scattering event and combining the solution with cloud BTDFs from the precomputed LUT, we can efficiently compute the diffuse radiances for each photon path. The solar radiances at the land surface are given by the total values of the radiances from all photon paths. The irradiances for various wavelength bands can then be computed for both horizontal and inclined surfaces.

Table 1: Possible Paths of Photons Transmitted through the Atmosphere

Path	Upper Clear Layer	Cloud	Lower Clear Layer
1	S	D	D
2	D	S	D
3	D	D	S
4	D	S	S
5	S	D	S
6	S	S	D
7	D	D	D
8	S	S	S

3 RESULTS

Figure 2 shows the spectral POA irradiances computed using the FARMS-NIT for an atmosphere with a water cloud. The cloud optical thickness and effective particle size are 1 and 10 µm, respectively, when the solar zenith angle is 45º. The spectral POA irradiances in the 2,002 wavelength bands are simulated over two surfaces where the tilt angles, β, are 0º and 45º. The figure shows that the PV panel with 45º tilt receives significantly more solar radiation than the horizontal PV panel.

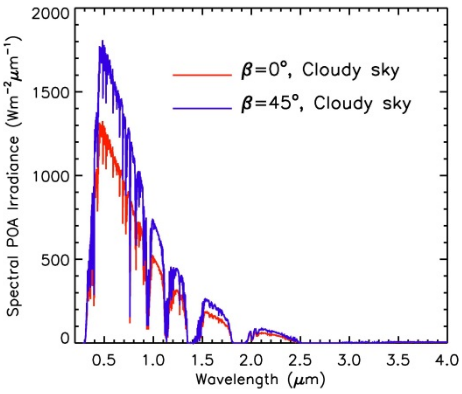

Figure 2: Spectral POA irradiances for an atmosphere with a water cloud. The solar zenith angle is 45º, and the surface albedo is 0. The cloud optical thickness and effective particle size are 1 and 10 µm, respectively.

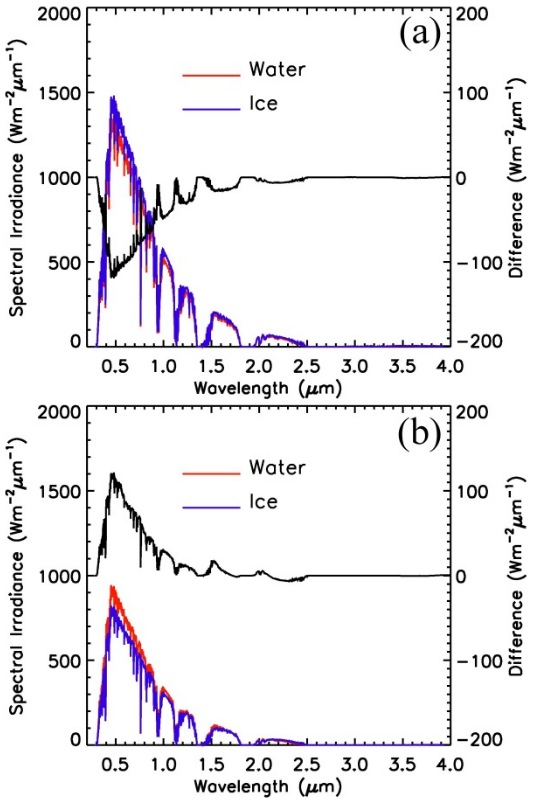

Figure 3: GHI simulated using FARMS-NIT when the solar zenith angle is 45° and surface albedo is 0.1. Clouds have optical thicknesses of (a) 1 and (b) 5 with an effective particle size of 10 µm. The black lines denote the difference in GHI between the water and ice clouds.

To understand the impact of ice and water cloud conditions on the simulations by FARMS-NIT, we computed cloudy-sky GHI when solar zenith angle is assumed as 45º. The clouds are composed of water droplets or ice crystals with an effective particle size of 10 µm.

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Figure 3 compares the GHI for optically thin and thick clouds. The black lines denote the difference in GHI between the water and ice clouds. For single-scattering events, ice crystals have more significant scattering than water droplets in the forward direction because of more diffraction. Ice crystals also have stronger backward scattering because of their nonspherical geometries and the relative internal and external reflections. Figure 3 shows that the GHIs of ice clouds are more than water clouds when the clouds are thin due to the increase in forward scattering by ice cloud particles; however, the forward scattering becomes less important for thick clouds when more solar radiation is reflected back to the space by ice crystals. As a result, the GHIs of water clouds are more than ice clouds in Fig. 3b.

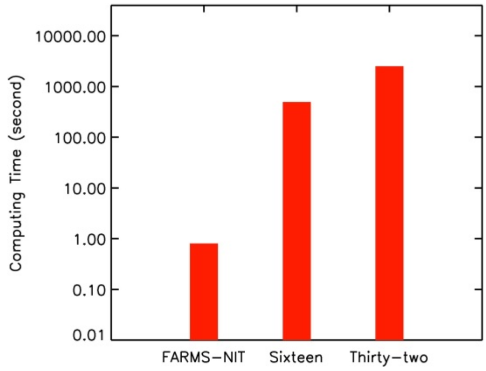

Figure 4: Computational time of FARMS-NIT and LibRadtran with 16 and 32 streams for computing spectral irradiances in 2,002 wavelengths.

Figure 4 shows the computational time for simulating spectral irradiances in 2,002 wavelengths. The cloudy-sky irradiances were computed using FARMS-NIT and a radiative transfer model for meteorology, LibRadtran. It is found that LibRadtran with 16- and 32-stream approximations consume 492 and 2,493 seconds for the computation, whereas FARMS-NIT uses only ~0.8 second. For a clear-sky condition, the computational time of FARMS-NIT can be further reduced because it considers less independent events than the cloudy-sky conditions.

4 CONCLUSIONS

In this study, we developed a new model to efficiently compute spectral POA irradiances over both horizontal and inclined surfaces. The spectral solar radiances and irradiances were numerically derived by considering all possible photon paths in the atmosphere. Our results indicate that this new model can effectively demonstrate the spectral structure of cloudy-sky solar radiation. Note that a new clear-sky spectral model is also desired because the current models cannot precisely compute clear-sky radiances for the possible photon paths. The accuracy of the clear-sky and cloudy-sky models are estimated using state-of-the-art radiative transfer models and surface observations. Additonally, the performance of the spectral irradiance models depends on the computational capabilities. Further efforts are underway to significantly improve the computational efficiency of the new model by parameterizing the LUT of cloud BTDF or applying advanced search technology.

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