Fast All-sky Radiation Model for Solar Applications (FARMS): A Brief Overview of Mechanisms, Performance, and Applications

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ABSTRACT: Solar radiation can be computed using radiative transfer models, such as the Rapid Radiation Transfer Model (RRTM) and its general circulation model applications (RRTMG), and used for various energy applications. Due to the complexity of computing radiation fields in aerosol and cloudy atmospheres, simulating solar radiation can be extremely time-consuming, though many approximations, e.g., two-stream approach and delta-M truncation scheme, can be utilized. To provide a new fast option for computing solar radiation, we developed the Fast All-sky Radiation Model for Solar applications (FARMS) by parameterizing the simulated diffuse horizontal irradiance and direct normal irradiance for cloudy conditions from RRTM runs using sixteen-stream discrete ordinates radiative transfer method. The solar irradiance at the surface was simulated by combining the cloud irradiance parameterizations with a fast clear-sky model, REST2. To understand the accuracy and efficiency of the newly developed fast model, we analyzed FARMS runs using cloud optical and microphysical properties retrieved using GOES data from 2009–2012. The global horizontal irradiance for cloudy conditions was simulated using FARMS and RRTMG with a two-stream approximation and compared to measurements taken from the U.S. Department of Energy's Atmospheric Radiation Measurement Climate Research Facility Southern Great Plains site. Our results indicate that the accuracy of FARMS is comparable to or better than the two-stream approach; however, FARMS is approximately 400 times more efficient because it does not explicitly solve the radiative transfer equation for each individual cloud condition. Radiative transfer model runs are computationally expensive, but this model is promising for broad applications in solar resource assessment and forecasting. It is currently being used in the National Solar Radiation Data Base, which is publicly available from the National Renewable Energy Laboratory at http://nsrdb.nrel.gov.
Keywords: Radiative transfer, solar energy

1. Purpose and Approach

An atmospheric radiative transfer (RT) model simulates light scattering and absorption within air molecules, aerosols, and clouds by numerically solving for the transmission of electromagnetic radiation in the Earth's atmosphere; consequently, it has broad applications in many fields of science and industry. The radiation computed by broadband RT models in the solar region provides quantitative information on the solar resource at specific locations and is required by people endeavoring to make effective use of solar energy. RT computations for cloudy skies are time-consuming because of the complexity in solving the RT equation. Although the two-stream approximation has been applied to solar resource assessment and forecasting, the increasing spatial and temporal resolutions of satellite retrievals as well as general circulation model and numerical weather prediction experiments demand RT models with significantly higher efficiency. Rapid development of satellite remote sensing has led to the corresponding development of fast cloudy-sky RT models aimed at simulating upwelling radiances for specific satellite channels (forward RT models); however, there is still a need to develop fast models that efficiently simulate all-sky solar irradiance at the land surface.

The Fast All-sky Radiation Model for Solar Applications (FARMS) solves for solar radiation under all-sky conditions—i.e., clear, cloudy overcast, and partially cloudy skies. The clear-sky solar radiation in the direct and diffuse directions are computed by REST2 [1] because it has been proven to be computationally efficient yet reasonably accurate. The commonly used single-layer cloud model [2, 3] is assumed as a first-order approximation to derive solar radiation under a cloudy sky. The light scattering and absorption by clouds are assumed as occurring at the top of the atmosphere to simplify the formulation and may result in minor uncertainties in simulating solar radiation at visible wavelengths. The uncertainties may not be ignorable for extreme cloud conditions—e.g., opaque clouds—but these are less interesting for solar energy applications.

The Rapid Radiative Transfer Model (RRTM) [4, 5] with sixteen-stream Discrete Ordinates Radiative Transfer (DISORT) [6] has been shown to produce radiative transfer calculations of high accuracy when compared to observations. Therefore, the sixteen-stream RRTM is used to compute a lookup table (LUT) of cloud transmittance for diffuse flux under all possible cloud conditions. The LUT is parameterized using an exponential function of solar zenith angle, cloud optical thickness, and particle size. Similar to transmittance, cloud reflectance for diffuse flux can also be simulated using RRTM with sixteen-stream DISORT. The cloud transmittance and reflectance are combined with those for clear-sky conditions to simulate the all-sky solar radiation at the land surface.

2. Method

Figure 1 shows the flowchart of FARMS. The LUTs of cloud transmittance and reflectance of irradiance are computed for both water and ice clouds. To simplify the application and reduce the computing time, the LUTs are parameterized by functions of solar zenith angles and cloud microphysical and optical properties. A clear-sky radiative transfer model, REST2, and atmospheric properties are used to compute the light scattering and absorption by aerosols and trace gases in the atmosphere. By utilizing REST2 and LUTs of cloud transmittances and reflectances precomputed by RRTM, FARMS is developed to simulate surface radiation for solar applications. The all-sky surface radiation is calculated by accounting for the influences of the clear-sky atmosphere, clouds, and the multiple reflections between cloud and land surface. Compared to previous models, this model is much more efficient yet provides very high accuracy.

3. Results

RRTM with sixteen-stream DISORT is used as a benchmark to simulate cloud total transmittances for all possible cloud conditions. FARMS and the RRTM for global circulation modeling (RRTMG) with a two-stream approximation are used to perform the same computations and evaluated using cloud transmittances from the sixteen-stream approximation. As shown in Table 1, it is found that both the two-stream approximation and FARMS show reasonable performance in computing cloud transmittance under clear and cloudy conditions. The percent errors (PEs) of FARMS are 0.0294% and 2.828% for typical water and ice clouds, respectively. FARMS significantly reduces PE and mean bias error (MBE) compared to the two-stream approximation, whereas its absolute percent error (APE) and mean absolute error (MAE) are slightly smaller. The comparison between satellite-based retrievals of atmospheric properties and surface measurements of solar radiation can also evaluate the accuracy of FARMS. As shown in Table 1, the PE and MBE for the FARMS computation of global horizontal irradiance (GHI) (-1.8936% and -5.4068 W/m^2, respectively) are much better than those of the two-stream approximation (-7.109% and -20.2983 W/m^2, respectively). The two-stream approximation and FARMS perform similarly when evaluated using APE, MAE, and root mean square error (RMSE).

We compare the computing time of FARMS to the two-stream approximation and RRTM with four- to 16-stream approximations for the surface radiation over the Atmospheric Radiation Measurement (ARM) Southern Great Plains (SGP) site. The computing time associated with FARMS and RRTMG is 2 seconds and 12 minutes and 32 seconds, respectively. The computing time for RRTM with sixteen-stream approximation is 2 hours and 2 minutes. Thus, for computations that result in similar accuracy levels, FARMS can dramatically reduce the computing time.

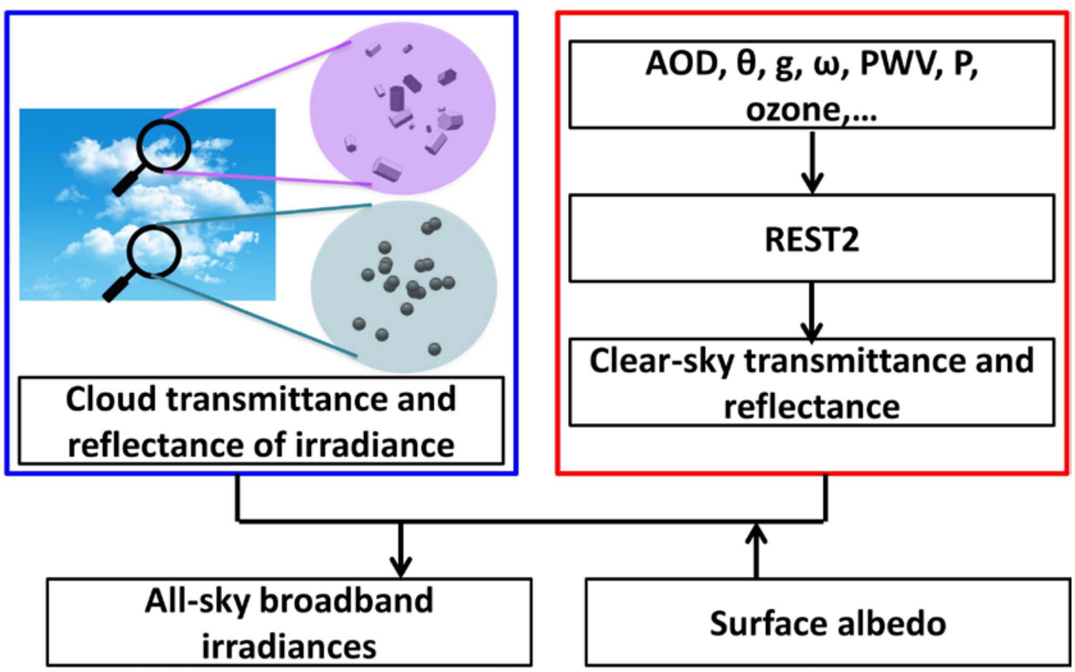

Figure 1. Flowchart of FARMS.

Table 1. Statistics of PE, APE, MBE, MAE, and RMSE of simulated cloud transmittance and GHI using two-stream approximation and FARMS.

RT Model	PE (%)	APE (%)	MBE	MAE	RMSE
Transmittance for Water Cloud					
Two-Stream	3.7195	4.6311	0.0156	0.0195	0.0319
FARMS	0.0294	2.9558	0.0012	0.0124	0.0165
Transmittance for Ice Cloud					
Two-Stream	7.0986	7.0986	0.0289	0.0289	0.0319
FARMS	2.8280	5.3852	0.0115	0.0220	0.0268
RT Model	PE (%)	APE (%)	MBE (W/m^2)	MAE (W/m^2)	RMSE (W/m^2)
GHI over ARM SGP Site					
Two-Stream	-7.109	31.7935	-20.2983	90.7798	132.749
FARMS	-1.8936	31.886	-5.4068	91.044	130.286

4. Conclusions

We have developed a fast all-sky radiative transfer model, FARMS, that has accuracy comparable to a two-stream radiative transfer model but is nearly 400 times computationally faster. This model is expected to be widely used in various applications that require rapid computations of solar radiation at the earth's surface under all atmospheric conditions. The model is currently being used to compute solar radiation for the National Solar Radiation Database (http://nsrdb.nrel.gov), which provides 4-km half-hourly resolution solar data for a 17-year period covering 1998–2014. The FARMS model is also expected to be included as an option in the version of the Weather Research and Forecasting model that is specially designed to produce accurate solar forecasting.

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