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5 1 **A Fast All-sky Radiation Model for Solar applications (FARMS): Algorithm**
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Abstract

Radiative transfer (RT) models simulating broadband solar radiation have been widely used by atmospheric scientists to model solar resources for various energy applications such as operational forecasting. Due to the complexity of solving the RT equation, the computation under cloudy conditions can be extremely time consuming though many approximations (e.g. two-stream approach and delta-M truncation scheme) have been utilized. Thus, a more efficient RT model is crucial for model developers as a new option for approximating solar radiation at the land surface with minimal loss of accuracy. In this study, we developed a fast all-sky radiation model for solar applications (FARMS) using the simplified clear-sky RT model, REST2, and simulated cloud transmittances and reflectances from Rapid Radiation Transfer Model (RRTM) with a sixteen-stream Discrete Ordinates Radiative Transfer (DISORT). Simulated lookup tables (LUTs) of cloud transmittances and reflectances are created by varying cloud optical thicknesses, cloud particle sizes, and solar zenith angles. Equations with optimized parameters are fitted to the cloud transmittances and reflectances to develop the model. The all-sky solar irradiance at the land surface can then be computed rapidly by combining REST2 with the cloud transmittances and reflectances. This new RT model is more than 1000 times faster than those currently utilized in solar resource assessment and forecasting since it does not explicitly solve the RT equation for each individual cloud condition. Our results indicate the accuracy of the fast radiative transfer model is comparable to or better than two-stream approximation in term of computing cloud transmittance and solar radiation.

1. Introduction

Atmospheric radiative transfer (RT) models, e.g., Discrete Ordinates Radiative Transfer (DISORT)(Stamnes *et al.*, 1988), Rapid Radiative Transfer Model (RRTM)(Mlawer *et al.*, 1997), MODerate resolution atmospheric TRANsmission (MODTRAN)(Berk *et al.*, 1998), 6S(Kotchenova *et al.*, 2006), and Community Radiative Transfer Model (CRTM)(Chen *et al.*, 2008), simulate light scattering and absorption by air molecules, aerosols and clouds, numerically solve the RT equation for the Earth's atmosphere and consequently have broad applications in many fields of science and industry. Narrow- and broadband RT models for visible through microwave wavelengths are often used to simulate upwelling and downwelling radiances and irradiances and thereby retrieve aerosol, cloud, and other atmospheric properties from satellite- or surface-based remote sensing measurements (Hsu *et al.*, 2006; Long *et al.*, 2006; Min and Harrison, 1996; Minnis *et al.*, 2011; Nakajima and King, 1990; Sengupta and Ackerman, 2003; Strow *et al.*, 2003; Wei *et al.*, 2004; Xie, 2010; Xie and Liu, 2013; Xie *et al.*, 2014; Xie *et al.*, 2009; Xie *et al.*, 2012b). Solar radiation computed by broadband RT models provides quantitative information on solar resource at specific locations and is needed for the development of solar energy applications (Sengupta *et al.*, 2010; Sengupta *et al.*, 2014; Sun *et al.*, 2012; Sun *et al.*, 2014; Yang *et al.*, 2006). For the efficient use and management of solar energy on the electricity grid, RT models with cloud properties from satellites and cloud motion from NWP models are used to produce short-term solar forecasts (Lorenz *et al.*, 2009; Perez *et al.*, 2010).

Broadband RT models particularly designed for clear skies, i.e. cloudless conditions, are of great interest for solar applications since they are usually associated with the maximum available solar resource during a certain period of time. Although high-spectral-resolution RT

models, e.g. line-by-line models(Clough *et al.*, 1992), provide rigorous solutions of clear-sky solar irradiance by accounting for the integration of spectral absorption in the atmosphere, a number of clear-sky RT models have been developed using parameterizations of broadband solar transmittance from surface observations or model simulations in spectral bands(Atwater and Ball, 1978; Bird and Hulstrom, 1981; Gueymard, 1989; 2003; 2008; Hoyt, 1978; Ineichen, 2008; Lacis and Hansen, 1974; Rigollier *et al.*, 2000). Those clear-sky RT models are efficient and heavily used in solar applications despite their limited capabilities to compute spectral or broadband radiation at various levels of the atmosphere beyond the land surface.

Compared to clear-sky RT models, RT computations under cloudy skies are considerably more computationally expensive due to the complexity of solving the RT equation (Chandrasekhar, 1950; Liou, 2002; Wendisch and Yang, 2012). Two-stream approximation and its numerous variants, e.g. Eddington approximation, modified Eddington, quadrature, and delta function (Irvine, 1965; 1968; Meador and Weaver, 1979; Sagan and Pollack, 1967), are well-known as efficient solutions of the RT equation under cloudy conditions. While two-stream approximation has been applied to solar resource assessment and forecasting (Pinker and Laszlo, 1992; Ruiz-Arias *et al.*, 2012; Skamarock and Klemp, 2008; Skamarock *et al.*, 2005), a number of challenges exist for solar energy applications. For example, reducing the computational burden due to the increasing spatial and temporal resolutions of satellite data and GCM and NWP experiments demands RT models with a significantly reduced computational burden than the two-stream approximation can provide. Moreover, the expansion of discrete ordinate streams (Chandrasekhar, 1950) can lead to improved accuracy in simulating radiation compared to two-stream approximation, especially at visible wavelengths (Ding *et al.*, 2009; Meador and Weaver, 1979; Qiu, 2001; Xie *et al.*, 2006; Yan and Stamnes, 2003).

Rapid development of satellite remote sensing has accelerated the studies of fast cloudy-sky RT models aimed at simulating the upwelling radiances (also known as forward RT models) for specific satellite channels (Minnis *et al.*, 2011; Niu *et al.*, 2007; Wang *et al.*, 2011; Wang *et al.*, 2013; Wei *et al.*, 2004; Xie *et al.*, 2012b). Compared to rigorous RT models, the fast RT models can substantially reduce the computational time at the expense of accuracy since they often carry pre-computed lookup tables (LUTs) of cloud bi-directional reflectance distribution function (BRDF) and bi-directional transmittance distribution function (BTDF). The existing fast RT models for cloudy-skies are not favorable candidates for solar applications because (1) they are developed for narrow satellite channels that are sensitive/insensitive to the amount of aerosol, cloud or specific trace gases while solar applications desire broadband radiation in the complete solar region; (2) they need significantly more computational time to compute angular-dependent radiances and convert them to downwelling irradiance for solar applications; (3) absorption by trace gases under clouds is more important in the simulation of downwelling radiation. However, the application of LUTs for cloud BRDF and BTDF can be used as guide in the development of fast RT models for solar applications.

In this study, we developed a fast all-sky radiation model for solar applications (FARMS) to provide users a new option of efficiently simulating solar irradiance at the land surface with less than 5% overall uncertainty compared to surface observations. This new model takes the advantage of the existing RT models by precomputing cloud transmittance and reflectance. Instead of directly using LUTs that require substantial computer memory and data storage, the cloud transmittances and reflectances are parameterized to increase computational efficiency. The computational time for the new model can be significantly reduced compared to two-stream approximation since the complex solution of solving the RT equation is not involved. Moreover,

FARMS uses the computation from more discrete ordinate streams than two-stream approximation, which can potentially improve its accuracy.

The rest of this paper is organized as follows. The analytical formulation of FARMS and the parameterization of the LUTs for cloud reflectances and transmittances are presented in Section 2. The accuracy and computational efficiency of FARMS are compared to the state-of-the-art RT models and discussed in Section 3. Conclusions can be found in Section 4.

2. Methodology

Figure 1 is a flowchart demonstrating the computation of solar radiation using FARMS. FARMS calculates broadband solar radiation under all-sky conditions, i.e. clear, cloud overcast, and partially cloudy skies. The clear-sky solar radiation in the direct and diffuse directions are computed by REST2 (Gueymard, 2008) because it has been proved to be computationally efficient yet highly accurate. The formulation of REST2 model is detailed in Gueymard (2008). The rest of this section introduces the formulation of overcast cloud conditions since solar radiation under a partially cloudy sky can be derived from the measurements of cloud fraction and a weighted average of the radiation from the clear and cloud overcast conditions. For instance, global horizontal irradiance (GHI) and direct normal irradiance (DNI) for a partially cloudy sky can be given as

$$GHI = fGHI_{cld} + (1 - f)GHI_{clr} \quad (1a)$$

$$DNI = fDNI_{cld} + (1 - f)DNI_{clr} \quad (1b)$$

where f denotes cloud fraction, and “cld” and “clr” represent cloud overcast and clear-sky conditions, respectively.

2.1 Analytical formulation

To derive solar radiation under a cloudy sky, the commonly used single-layer cloud model (Coakley *et al.*, 2005; Kattawar *et al.*, 2016; Lawless *et al.*, 2006; Ramanathan, 1987) is assumed as a first-order approximation in the analytical formulation below. For simplification of the formulation, the light scattering and absorption by clouds are assumed as occurring at the top of the atmosphere (TOA), which may result in $\sim 1 \text{ W/m}^2$ uncertainties on average in simulating solar radiation at the land surface. The uncertainties in solar radiation associated with this assumption are tested and discussed in Appendix A. Also note that only the scattering and absorption by cloud particles are considered within the cloud layer while the absorption by the atmospheric gases is computed in other parts of the atmosphere. As the atmospheric gases are optically thin compared to the total atmospheric column the diffuse absorption by the atmospheric gases can be considered negligible.

Under the above assumptions, the direct solar flux in the downwelling direction at the surface can be given by

$$F_d = \mu_0 F_0 T_{dd}^{cld} T_{dd}^{clr} \quad (2a)$$

where μ_0 is the cosine of the solar zenith angle, F_0 is the radiative flux at the TOA, T_{dd}^{cld} is the transmittance of the cloud for direct incident radiation and direct outgoing radiation after scattering by clouds, and T_{dd}^{clr} is the transmittance of the clear-sky atmosphere relative to direct incident and output fluxes. Thus, the direct normal irradiance (DNI) is

$$DNI = \frac{F_d}{\mu_0} = F_0 T_{dd}^{cld} T_{dd}^{clr} \quad (2b)$$

In the derivation below, F represents the radiative flux in the downwelling direction. The first character of the subscript indicates whether the incident radiation we consider is direct (“d”) or diffuse (“u”). The second character of the subscript represents the state of the outgoing radiation

after atmospheric scattering. For example, “dd” represents the incident and outgoing fluxes that are both direct. Similarly subscript, “uu”, represents the incident and outgoing fluxes that are both diffuse. The subscript, “du”, represents direct incidence and diffuse outgoing.

The first order total downward flux is

$$F_1 = \mu_0 F_0 T_{dd}^{cld} T_{dt}^{clr} + \mu_0 F_0 T_{du}^{cld} T_{uu}^{clr} \quad (3)$$

where T_{dt}^{clr} is the transmittance of the clear-sky atmosphere for direct incidence and total outgoing flux. Thus,

$$T_{dt}^{clr} = T_{dd}^{clr} + T_{du}^{clr} \quad (4)$$

In the computation of T_{uu}^{clr} , the transmitted diffuse through the cloud layer is assumed isotropic though cloud transmittance is exactly computed. Thus, the isotropic assumption only slightly affects the computation of transmittance of the atmosphere. Since radiance, I , is independent of zenith angle, T_{uu}^{clr} can be approximated by

$$\begin{aligned} T_{uu}^{clr} &\approx \frac{\int_0^1 \mu T_{dd}^{clr}(\mu) d\mu}{\int_0^1 \mu d\mu} \\ &= 2 \int_0^1 \mu T_{dd}^{clr}(\mu) d\mu \end{aligned} \quad (5)$$

where μ is the cosine value of the zenith angle for an individual solar beam.

The total downwelling flux (or the global horizontal irradiance (GHI)) for all surface conditions is given by considering the multiple reflectance between land surface and cloud:

$$\begin{aligned} F_{total} &= F_1 + F_1 R_s R_{uu}^{clr} + F_1 R_s T_{uu}^{clr} R_{uu}^{cld} T_{uu}^{clr} + \dots \\ &= F_1 + F_1 R_s (R_{uu}^{clr} + R_{uu}^{cld} T_{uu}^{clr^2}) + \dots \\ &= F_1 \left[1 - R_s (R_{uu}^{clr} + R_{uu}^{cld} T_{uu}^{clr^2}) \right]^{-1} \end{aligned} \quad (6)$$

where R_s is surface reflectance. R_{uu}^{clr} and R_{uu}^{cld} are aerosol and cloud reflectances for diffuse fluxes, respectively. It can be seen that the second term in the right hand side of Eq.(6) represents the first order downward flux reflected by land surface and reflected back to surface by the aerosol in the atmosphere. The third term on the right hand side of Eq.(6) denotes the first order downward flux reflected by both land surface and cloud, that comes back to the land surface.

Then the diffuse horizontal irradiance (DHI) can be given by

$$DHI = F_{total} - F_d \quad (7)$$

In Eqs. (2-7), T_{dd}^{clr} , T_{du}^{clr} , T_{uu}^{clr} , and R_{uu}^{clr} can be computed by REST2 model for a non-reflecting land surface.

The cloud transmittance for direct flux can be given on the basis of the Beer-Bouguer-Lambert law for extinction (Liou, 2002):

$$T_{dd}^{cld} = e^{-\tau / \mu_0} \quad (8)$$

where τ is the cloud optical thickness in the solar region. To numerically solve for solar radiation in the direct and diffuse directions, i.e., Eqs.(2) and (6), T_{du}^{cld} and R_{uu}^{cld} are computed and parameterized in sections 2.2 and 2.3, respectively.

2.2 Parameterization of diffuse transmittances of clouds

To circumvent the complex solutions of the RT equation, a LUT of cloud transmittance for diffuse flux, T_{du}^{cld} , is simulated using RRTM (Mlawer *et al.*, 1997; Oreopoulos and Barker, 1999) with sixteen-stream DISORT (Stamnes *et al.*, 1988) for all possible cloud conditions. RRTM utilizes the parameterizations of cloud optical properties over fourteen contiguous bands and simulates radiation in the individual bands as well as the integrated shortwave region.

T_{du}^{cld} can be simply computed by placing a cloud layer at the top of the TOA and considering the downwelling irradiance above and under the cloud layer. In this study, T_{du}^{cld} is computed for cloud optical thickness $\tau=0.0001, 0.01, 0.1, 0.2, \dots, 0.5, 1.0, \dots, 3.0, 4.0, \dots, 8.0, 10.0, \dots, 20.0, 25.0, \dots, 50.0, 60.0, \dots, 100.0, 140.0, \dots, 300.0$, cloud effective particle size $D_e=5.0, 6.0, \dots, 10.0, 12.0, \dots, 30.0, 35.0, \dots, 60.0, 70.0, \dots, 120.0$ μm and $\mu_0=0.02, 0.04, \dots, 1.0$. The LUT is computed as a function of cloud optical thickness as it directly represents the extinction of solar radiation and is often retrieved by satellite-based measurements of clouds. To adapt FARMS to models that provide cloud microphysical variables rather than optical thickness, cloud optical thickness can be obtained from cloud liquid water path (LWP) or ice water path (IWP) and effective particle size information from formulas such as

$$\tau = LWP(a + b/r_e) \quad (9)$$

where r_e is effective radius of water clouds, a and b are parameters given by Hu and Stamnes (1993). Details on the determination of cloud optical thickness from LWP or IWP are not restated here as they have been extensively introduced by Hu and Stamnes (1993), Fu (1996), Matrosov et al. (2003), and Xie et al. (2012a). Cloud optical thickness is calculated externally and used as an input to FARMS. Therefore, cloud optical thickness may or may not be influenced by effective particle size depending on how it is computed. The cloud scattering properties, including single scattering albedo and asymmetry factor, are determined by cloud effective particle size and parameterized by Hu and Stamnes (1993) and Fu (1996). For clouds composed of water droplets, the cloud effective particle size is defined as

$$D_e = 2 \times r_e \quad (10)$$

For ice clouds, the definition of cloud effective particle size follows the description of Fu (1996).

Figure 2 illustrates the simulated T_{du}^{cld} for water and ice clouds as functions of cloud optical thickness and solar zenith angle. It is seen that the diffuse transmittances increase with cloud optical thickness due to the increasing scattering by clouds when they are optically thin. The diffuse transmittances increase with optical thickness for values of τ from 0.2-5 and decrease after that. The cloud diffuse transmittances are also sensitive to solar zenith angle. When clouds are very thin, larger solar zenith angles lead to greater T_{du}^{cld} because of the longer path of the radiation in the cloud. Also, T_{du}^{cld} decreases with increasing solar zenith angle for thicker clouds. The effective particle sizes for the water and ice clouds are assumed to be 16 and 70 μm , respectively. Compared to cloud optical thickness and solar zenith angle, the cloud particle size has lower impact on the radiation at visible wavelengths as demonstrated by previous studies (King *et al.*, 1996; Xie, 2010).

To reduce the computing burden of FARMS, T_{du}^{cld} should be parameterized as a function of solar zenith angle, cloud optical thickness and particle size since checking values from the LUT consumes considerable computational resource. As Fig. 2 clearly shows, the distribution of T_{du}^{cld} can be approximated by exponential functions. We parameterize T_{du}^{cld} in the form of

$$T_{du}^{cld} = f(D_e, \tau, \mu_0) T_{du,p}^{cld}(D_e, \mu_0) \exp \left[- \frac{\left(\log_{10} \frac{\tau}{\tau_p(D_e, \mu_0)} \right)^2}{D(\mu_0)} \right] \quad (11)$$

where τ_p is the cloud optical thickness as T_{du}^{cld} reaches its maximum, $T_{du,p}^{cld}(D_e, \mu_0)$ is the maximum of T_{du}^{cld} for each given solar zenith angle, $D(\mu_0)$ is a function that is related to the width

of T_{du}^{cld} , and $f(\tau, D_e, \mu_0)$ is a scaling factor that adjusts T_{du}^{cld} especially when cloud optical thickness is large.

For water clouds, the variables of Eq.(11) are parameterized as

$$\tau_p(D_e, \mu_0) = [2.885 + 0.002(D_e - 60)]\mu_0 - 0.007347 \quad (12a)$$

$$T_{du,P}^{cld}(D_e, \mu_0) = 0.7846[1 + 0.0002(D_e - 60)]\mu_0^{0.1605} \quad (12b)$$

$$D(\mu_0) = -0.644531\mu_0 + 1.20117 + 0.129807\mu_0^{-1} - 0.00121096\mu_0^{-2} + 1.52587 \times 10^{-7}\mu_0^{-3} \quad (12c)$$

$$f(\tau, D_e, \mu_0) = 1 + \sinh[0.012\mu_0(\tau - \tau_p(D_e, \mu_0))] \quad (12d)$$

where $\sinh$ denotes the hyperbolic sine function.

For ice clouds,

$$\tau_p(D_e, \mu_0) = \begin{cases} 2.8487\mu_0 - 0.0029 & \text{for } D_e \leq 26\mu m \\ [2.8355 + 0.006(100 - D_e)]\mu_0 - 0.00612 & \text{for } D_e > 26\mu m \end{cases} \quad (13a)$$

$$T_{du,P}^{cld}(\mu_0) = 0.756\mu_0^{0.0883} \quad (13b)$$

$$D(\mu_0) = -0.0549531\mu_0 + 0.617632 + 0.17876\mu_0^{-1} - 0.002174\mu_0^{-2} \quad (13c)$$

$$f(\tau, D_e, \mu_0) = 1 + \sinh[0.01\mu_0(\tau - \tau_p(D_e, \mu_0))] \quad (13d)$$

Details on parameterization of the functions in Eq. (11) can be found in Appendix B.

The solid lines of Fig.2 represent the parameterization using Eqs.(11-13). A generally good agreement is shown though larger differences can be found for extremely thin or thick clouds. Note that cloud transmittance has minor impacts on solar radiation when the cloud is extremely thin or thick. Thus, FARMS should have reasonable accuracy when it is used to

simulate solar irradiance. Further evaluation on the performance of FARMS is discussed in section 3.

2.3 Parameterization of diffuse reflectances by clouds

Similar to T_{du}^{cld} , R_{uu}^{cld} can also be simulated using RRTM with sixteen-stream DISORT when the incident radiation is assumed isotropic. Figure 3 shows the simulated R_{uu}^{cld} as functions of cloud optical thickness and particle size. For both water and ice clouds, R_{uu}^{cld} is slightly sensitive to D_e , which can then be parameterized using simple functions of cloud optical thickness.

For water cloud, the simulated R_{uu}^{cld} can be fitted using

$$R_{uu}^{cld} = \begin{cases} 0.107359\tau & \text{for } \tau < 1 \\ 1.03 - \exp\left[-\frac{(0.5 + \log_{10} \tau)^2}{3.105}\right] & \text{for } \tau \geq 1 \end{cases} \quad (14a)$$

For ice cloud, R_{uu}^{cld} can be given by

$$R_{uu}^{cld} = \begin{cases} 0.094039\tau & \text{for } \tau < 1 \\ 1.02 - \exp\left[-\frac{(0.5 + \log_{10} \tau)^2}{3.25}\right] & \text{for } \tau \geq 1 \end{cases} \quad (14b)$$

It is obvious from the solid lines of Fig.3 that the parameterization accurately represents the average of R_{uu}^{cld} over all the D_e s.

3. Performance evaluation

Two-stream approximation (Irvine, 1965; 1968; Meador and Weaver, 1979; Sagan and Pollack, 1967) adopted by RRTM for GCM applications (also known as RRTMG) and the

RRTM with an expansion of discrete ordinate streams provide time-efficient solutions of the RT equation and have been widely used in the simulation of solar radiation (Pinker and Laszlo, 1992; Ruiz-Arias *et al.*, 2012; Skamarock and Klemp, 2008; Skamarock *et al.*, 2005; Xie and Liu, 2013; Xie *et al.*, 2012a). To understand the performance of FARMS, we compare the accuracy and efficiency of the two-stream approximation, RRTM and FARMS for the same computations.

3.1 Accuracy in the computation of cloud transmittance

RRTM can compute solar radiation with a selection of discrete ordinate streams ranging from four to sixteen. Although the use of more discrete ordinate streams can provide improved accuracy of solar radiation, Ding *et al.*(2009) discovered that four and thirty-two terms of Legendre polynomials in the cloud scattering phase function are normally sufficient for DISORT to compute radiance at infrared and visible wavelengths, respectively. However, the uncertainty related to the number of discrete ordinate streams can be averaged down when irradiance is developed from the integration of radiance over space (Li *et al.*, 2015).

We use RRTM with sixteen-stream DISORT as a benchmark to simulate cloud total transmittances, i.e. T_{dt}^{cld} , for all possible cloud conditions as described in section 2.2. The same computations are performed using RRTMG which uses the two-stream approximation and FARMS and evaluated using those from the sixteen-stream approximation. Figure 4 shows the relative errors of water cloud transmittance from two-stream approximation and FARMS as compared with the sixteen-stream approximation. The red and blue colors in the figure denote under- and over-estimation of the transmittance from the sixteen-stream approximation, respectively. Compared to the sixteen-stream approximation, two-stream approach significantly

overestimates transmittances for large solar zenith angles, unlike FARMS which is significantly more accurate. For small solar zenith angles, the transmittances are slightly underestimated by two-stream approximation when the clouds are thick. This underestimation becomes much more obvious when using FARMS as can be also seen in Fig.2a. The parameterization of FARMS slightly underestimates the transmittances though the relative differences are large due to the low transmittances.

Figure 5 is the same as Fig. 4 except for ice clouds with $D_e=70\mu\text{m}$. Similar to water cloud transmittances, those of ice clouds are significantly overestimated by two-stream approximation for large solar zenith angles. For small solar zenith angles, two-stream approximation also increasingly overestimates ice cloud transmittances with increasing cloud optical thickness. In Fig. 5b, uncertainties of ice cloud transmittance occur for large solar zenith angles or when cloud is thick. Since those solar and cloud conditions are associated with low solar radiation, they are normally less important compared to regions associated with higher solar energy.

To numerically evaluate the overall performance of two-stream approximation and FARMS, we consider various statistical measures including percent error (PE), absolute percent error (APE), mean bias error (MBE), mean absolute bias error (MAE), and root-mean-square error (RMSE) of simulated cloud transmittance and GHI defined as follows,

$$PE = \frac{\sum_{i=1}^n (x_m - x)}{\sum_{i=1}^n x} \quad (15a)$$

$$APE = \frac{\sum_{i=1}^n |x_m - x|}{\sum_{i=1}^n x} \quad (15b)$$

$$MBE = \frac{1}{n} \sum_{i=1}^n (x_m - x) \quad (15c)$$

$$MAE = \frac{1}{n} \sum_{i=1}^n |x_m - x| \quad (15d)$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^n (x_m - x)^2}{n}} \quad (15e)$$

where x represents cloud transmittance simulated by RRTM with sixteen-stream DISORT, x_m denotes the simulations using two-stream approximation or FARMS. Table 1 shows those statistics associated with the results of Figs. 4 and 5. It can be found that both two-stream approximation and FARMS have reasonable performance in computing cloud transmittance under frequent solar and cloud conditions. The PEs of FARMS are 0.0425% and 3.0987% for typical water and ice clouds, respectively. Compared to two-stream approximation, FARMS significantly reduces PE and MBE while its APE and MAE are slightly smaller.

3.2 Accuracy in the computation of solar radiation

The accuracy of FARMS can also be evaluated by comparing satellite-based retrievals of atmospheric properties and surface measurements of solar radiation. In FARMS, we use data from the AVHRR Pathfinder Atmospheres-Extended (PATMOS-x) algorithms (Heidinger *et al.*, 2013; Sengupta *et al.*, 2014) applied to the Geostationary Operational Environmental Satellite (GOES) data where the atmospheric properties for clear-sky RT models, e.g. 30-minute precipitable water vapor (PWV), were produced by the National Oceanic and Atmospheric Administration (NOAA)/National Centers for Environmental Prediction (NCEP). Since ozone has limited impact on solar radiation when clouds are present the ozone amount in the

atmosphere is assumed to be 300 DU in the absence of ozone from the PATMOS-x data,. In two-stream approximation, the clear-sky atmospheric profile follows the 1976 US Standard Atmosphere where the PWV values are scaled by the PATMOS-x data.

For both two-stream approximation and FARMS, the cloud microphysical and optical properties of the GOES data are available every 30 minutes for 4-km resolution pixels. Daily averaged aerosol optical depth (AOD) is derived from the Moderate Resolution Imaging Spectroradiometer (MODIS) and Multi-angle Imaging SpectroRadiometer (MISR) AOD product that is scaled using the surface-based Aerosol Robotic Network (AERONET) data (Sengupta *et al.*, 2014). The total AOD is used by FARMS to compute the clear-sky transmittance and reflectance as described by Gueymard (2008). The broadband shortwave surface albedo is given by a climatology using NASA's Modern-ERA Retrospective Analysis for Research and Applications (MERRA) data (Rienecker *et al.*, 2011).

The surface-based solar radiation, with a temporal resolution of 1 minute, is observed at the Atmospheric Radiation Measurement (ARM) Southern Great Plain (SGP) site in Oklahoma (Stokes and Schwartz, 1994). The solar radiation is then averaged over 30 minutes and collocated with the satellite products which are used as inputs to two-stream approximation and FARMS to simulate GHIs. Figure 6 demonstrates the comparison of the GHIs between the model simulations and ARM measurements where the colors represent the density of the data. A total number of 9669 scenarios associated with overcast cloudy conditions are selected during 2009-2012. It is obvious that the simulations from both two-stream approximation and FARMS have good agreement to the surface measurements. Based on Table 1, the PE and MBE for FARMS computation of GHI are -1.8936% and -5.4068 W/m², respectively, much better than two-stream approximation. Two-stream approximation and FARMS perform similarly when

evaluated by APE, MAE, and RMSE. Note that the uncertainties in Fig. 6 come from the satellite-based cloud property retrievals, other input uncertainties as well as the RT models.

Figure 7 demonstrates the monthly and daily mean GHIs from Fig. 6. Compared to ARM measurements, the model simulations generally under estimate GHI especially in winter. As two-stream approximation and FARMS slightly overestimate cloud transmittance, the bias in GHI is probably because the MERRA climatology data underestimates surface albedo when there is snow. Compared to two-stream approximation, the solar radiation from FARMS has better agreement with ARM surface measurements, which indicates FARMS has a better simulation of multiple reflectance between land surface and cloud.

3.3 Comparison of computing time

Figure 8a compares the computing time of FARMS, RRTMG with two-stream approximation and RRTM with the four- to sixteen-stream approximations for the cloud transmittances discussed in section 2.2. The computing time is recorded based on the computations using National Renewable Energy Laboratory's (NREL's) High Performance Computing (HPC) system which has 6912 Intel Xeon E5-2670 "SandyBridge" processors, 24192 Intel Xeon E5-2695v2 "IvyBridge" processors and 576 Intel Phi many-core co-processors providing a total capability of 1190 Trillion floating point calculations per second. During the computations of cloud transmittance, the efficiency for water and ice cloud do not show much difference. For all the water cloud conditions, two-stream approximation uses 31 minutes and 31 seconds on a single processor while sixteen-stream consumes 3 hours and 30 minutes. For the same computation, FARMS dramatically reduces the computing time to 0.018 seconds.

Figure 8b illustrates the computing time related to the surface radiation over the ARM SGP site. In addition to computing the radiative transfer within clouds, these computations also account for the light scattering and absorption by the clear sky and the multiple reflectance between cloud and land surface. FARMS, RRTMG with two-stream approximation and RRTM with sixteen-stream approximation use 2 seconds, 12 minutes and 32 seconds and 2 hours and 2 minutes, respectively. FARMS is not as efficient in computing solar radiation compared to cloud transmittance calculations as shown in Fig. 8a but is still over 300 times faster than two-stream approximation. This is because multiple computations of Eq.(5) is used to compute clear-sky transmittance for diffuse radiation. To further reduce the computing time of FARMS, a parameterization of Eq. (5) is required.

4. Concluding remarks

By utilizing a clear-sky radiative transfer model, REST2, and LUTs of cloud transmittances and reflectances pre-computed by RRTM, a fast all-sky radiative transfer model, FARMS, is developed to simulate surface radiation for solar applications. For simplicity in application and reducing the computing time, the LUTs are parameterized by exponential functions of solar zenith angles and cloud microphysical and optical properties. REST2 is used to compute the light scattering and absorption by aerosols and trace gases in the atmosphere. 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.

The performance of FARMS is evaluated using RRTMG with two-stream approximation and RRTM with four- to sixteen-stream approximations where the computation by the sixteen-stream approximation serves as a benchmark. It is found that two-stream approximation

overestimates cloud transmittance in large solar zenith angles unlike FARMS. Compared to the two- and sixteen-stream approximations, FARMS underestimates cloud transmittance for thick clouds. However, both FARMS and two-stream approximation show similar accuracy for the most cloud conditions of relevance to solar energy applications. The performance of FARMS has also been evaluated using measurements at the ARM SGP site. The solar radiation is simulated using the two-stream approximation and FARMS, with the cloud and other atmospheric properties being determined from satellite retrievals and reanalysis models. Compared to ARM measurements during 2009-2012, two-stream approximation and FARMS have similar performance in terms of APE, MAE, and RMSE. However, FARMS performs better than two-stream approximation in terms of PE and MBE. The comparison of the computing time indicates FARMS is much more efficient than other RT models used in weather, climate and solar energy applications. Thus, it can be used widely for various applications because of its accuracy and efficiency.

Several points are noteworthy. The recent emergence of solar energy as an alternative to the more conventional domestic energy sources has resulted in a demand for deriving global solar resource from satellite data. NREL has utilized GOES data and developed the National Solar Radiation Data Base (NSRDB) covering the North and South America at a resolution of 4km for every 30 minutes of 2005-2012 (Sengupta *et al.*, 2014). The cloudy-sky solar radiation from the NSRDB originally used a product of the Satellite Algorithm for Surface Radiation Budget (SASRAB) model (Pinker and Laszlo, 1992) where the relationship between solar reflectance and transmittance is given by a computation of two-stream technique (Joseph *et al.*, 1976). As discussed in section 3, FARMS demonstrates its potential to better accommodate the increasing spatial and temporal resolution from the next generation of satellites. Due to the

simplicity of the parameterization, FARMS also accommodates parallel computation, which further reduces the computing time. It is therefore currently being used as the RT model in the NSRDB. As two-stream approximation has been widely used in NWP models, e.g. the Weather Research and Forecasting (WRF) model (Skamarock *et al.*, 2005), other applications of FARMS might be those in NWP models to provide higher temporal resolution solar forecasting; efforts on updating the NWP models are underway on this. Typically, for efficiency, NWP models have a radiation time step that is an order of magnitude longer than its dynamical/microphysical time step, so the cloud-radiation interaction is time-sampling the clouds and not making full use of the resolved-cloud time variation. FARMS allows the surface radiation to respond to cloud changes at the full model time resolution when applied at the model's dynamical/microphysical time step. Finally, FARMS follows the wavelength range from RRTM, i.e. 0.2-12.2 μm , to consider the contribution from the broadband solar radiation. Since Photovoltaic (PV) technology is spectral sensitive (Argazzi *et al.*, 1994), future studies on the RT models for narrow spectral bands can serve as a theoretical framework for assessing the PV plant performance.

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Appendix A: The impact of cloud height on the simulation of solar radiation

For simplification of the formulation, the light scattering and absorption by clouds are assumed as occurring at the TOA. Thus, the absorption of trace gases within the cloud layer is considered under the cloud with the other part of the atmosphere. To numerically understand the uncertainty associated with this assumption, we simulated solar radiation over the ARM SGP site using two-stream approximation and cloud product introduced in section 3.2 where cloud heights and other properties are retrieved by the PATMOS-X algorithm. The whole atmosphere is divided into 90 layers in the two-stream approximation. The cloud whose physical thickness is assumed as 0.5 km is inserted into one of the layers based on cloud height. The solar radiation is also simulated using a cloud height of 20 km while all the other cloud properties, including cloud physical thickness, are kept the same. Figure A compares the simulated GHIs using different cloud heights where very tiny differences are shown for all cloud conditions. Over the 9669 scenarios, an averaged underestimation of 1.005 W/m^2 associated with the cloud height of 20 km is discovered. This is related to the overestimation of atmospheric absorption by the trace gases above realistic cloud layers. The impact of cloud height on solar radiation simulation is extremely small as the concentration of trace gases above clouds is significantly low and cloud physical positions only affect multiple reflections between cloud and land surface. Thus, compared to the other uncertainties, e.g., those in the retrieval of cloud microphysical and optical properties, the assumption of a cloud layer at the TOA has minor impact on the performance of FARMS.

Appendix B: Parameterization of the functions in Eq.(11)

To parameterize T_{du}^{cld} using exponential functions, it is important to accurately represent the functions in Eq.(11). Figure B1 demonstrates $T_{du,P}^{cld}$ as a function of D_e and μ_0 . It can be seen that $T_{du,P}^{cld}$ has near-linear relationships with μ_0 . D_e slightly impacts the magnitude of $T_{du,P}^{cld}$ for water clouds when μ_0 is large. For ice clouds (see Fig. B1(b)), $T_{du,P}^{cld}$ is almost independent on D_e . Considering a median D_e (60 μ m), we test multiple combinations of coefficients (see Eqs.(12b and 13b)) to best fit the numerical simulations of $T_{du,P}^{cld}$. Then we slightly adjust the coefficients for water cloud cases based on the dependence on D_e .

Figure B2 shows τ_p as a function of D_e and μ_0 . It is seen that τ_p increases with μ_0 while it is also sensitive to the variation of D_e . Similar to the parameterization of $T_{du,P}^{cld}$, τ_p can be also represented by functions of D_e and μ_0 (see Eqs.(12a and 13a)). Compared to $T_{du,P}^{cld}$, unavoidable uncertainty exists in the parameterization of τ_p as can be seen in Fig. B2. The impact of this uncertainty will be understood in the performance evaluation of Eq.(11) and the computation of solar radiation.

As $T_{du,P}^{cld}$ and τ_p are parameterized, we further test multiple coefficients of $D(\mu_0)$ to create best fit of the simulation of T_{du}^{cld} . As can be seen in Fig.2, the simulated T_{du}^{cld} is not perfectly asymmetrical around τ_p , especially for extremely small and great cloud optical thickness. To further reduce the uncertainty in Eq.(11), we introduce a scaling factor, $f(\tau, D_e, \mu_0)$, to adjust the magnitude of T_{du}^{cld} when the cloud is thick.

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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	3.7674	4.7164	0.0151	0.0189	0.0308
FARMS	0.0425	2.8716	0.0002	0.0115	0.0148
Transmittance for Ice cloud					
Two Stream	7.7293	7.7293	0.03	0.03	0.0325
FARMS	3.0987	5.6971	0.012	0.0221	0.027
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

FIGURES

Fig. 1 Flowchart of the computation of GHI, DNI and DHI using FARMS.

Fig.2 Simulated T_{du}^{cld} (dots) for (a) water clouds with $D_e=16 \mu m$ and (b) ice clouds with $D_e=70 \mu m$ as functions of cloud optical thickness and solar zenith angle and their parameterization (solid lines).

Fig.3 Simulated R_{uu} (dots) for (a) water clouds and (b) ice clouds as functions of cloud optical thickness and particle size and their parameterization (solid lines).

Fig.4 Relative error of water cloud T_{dt}^{cld} ($D_e=16 \mu\text{m}$) simulated by (a) two-stream approximation and (b) FARMS.

Fig.5 Relative error of ice cloud T_{dt}^{cld} ($D_e=70 \mu\text{m}$) simulated by (a) two-stream approximation and (b) FARMS.

Fig. 6 Comparison of GHIs between surface measurements over ARM SGP site and those simulated using satellite retrieval of cloud properties and (a) two-stream approximation and (b) FARMS.

Fig. 7 Comparison of (a) monthly mean and (b) daily mean GHIs between surface measurements over ARM SGP site and those simulated using satellite retrieval of cloud properties and two-stream approximation (blue) and FARMS (red).

Fig. 8 Computing time of (a) cloud transmittance and (b) surface radiation over ARM SGP site using FARMS, RRTMG with two-stream approximation and RRTM with the four- to sixteen-stream approximations.

Fig.A1 Comparison of GHIs over ARM SGP site simulated by two-stream approximation where cloud heights are given by PATMOS-X and a fixed value, 20 km.

Fig.B1 $T_{du,P}^{cld}$ for (a) water and (b) ice clouds as functions of D_e and μ_0 (dots) and parameterization (solid lines) using Eq.(13).

Fig. B2 τ_p for (a) water and (b) ice clouds as functions of D_e and μ_0 and parameterization (straight lines) using Eq.(13).