Solar Energy 135 (2016) 435–445

Contents lists available at ScienceDirect

Solar Energy

journal homepage: www.elsevier.com/locate/solener

A Fast All-sky Radiation Model for Solar applications (FARMS): Algorithm and performance evaluation

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ARTICLE INFO

Article history:
Received 15 September 2015
Received in revised form 31 May 2016
Accepted 1 June 2016
Available online 15 June 2016

Keywords:
Solar radiation
Radiative transfer model
Cloud

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, 2009, 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, 2014; Sun et al., 2012, 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

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http://dx.doi.org/10.1016/j.solener.2016.06.003
0038-092X/

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, 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 pre-computing 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

Fig. 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

$$\mathrm{GHI} = f\mathrm{GHI}_{cld} + (1-f)\mathrm{GHI}_{clr} \tag{1a}$$

$$\mathrm{DNI} = f\mathrm{DNI}_{cld} + (1-f)\mathrm{DNI}_{clr} \tag{1b}$$

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 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

$$F_d = \mu_0 F_0 T_{dd}^{cld} T_{dd}^{clr} \tag{2a}$$

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, DNI is given by

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

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