Stochastic Model for Shortwave Radiation Transfer in a Multiple-Layered Atmosphere: Surface Global Radiation in Cloudless Conditions

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Abstract. A two-flux method is presented, which describes propagation of solar radiation in the atmosphere as a random walk of diffuse photons among several atmospheric layers. Results are obtained in terms of absorption probabilities in each layer, at ground and within sky, allowing for making evident the interactions between the main atmospheric absorbers (ozone, aerosols and water vapor) and atmospheric structure. Application of this model to cloudless situations in the extreme cases of rural environment and high aerosol load by burning biomass shows good results when compared with SBDART code (+10 $W.m^{-2}$ systematic difference), and both differ from ground measurements of global radiation in about 30 to 50 $W.m^{-2}$. This difference could be lowered having a better definition of aerosol load during daytime. Global radiation is obtained by integration of monochromatic irradiances; it is observed that ME model performance is five times faster than DISORT.

Keywords: solar radiation, two-flux methods, stochastic processes, irradiance, Brazil
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1 INTRODUCTION

Solar radiation transfer in the atmosphere is described by a complex equation which uses to be reduced to a two-flux pair of equations describing upward and downward diffuse irradiances. Solutions for a multilayered atmosphere are especially useful for assessing profiles of radiative heating rate and evapotranspiration processes at ground level, within climate as well as general circulation models. For horizontally stratified atmosphere, Ceballos (1989) and Souza and Ceballos (1994) used concepts of stochastic processes to develop a method which is able to assess the vertical profile of absorption and transmission of solar radiation in atmospheres, describing radiation transfer as a random walk of diffuse photons between layers. It is equivalent to usual two-flux methods but works in a simplified way that allows for quick determination of vertical profiles of heating/cooling rates, as well as planetary reflectance and global radiation at ground level.

Previous tests with this model considered mainly monochromatic radiation. Present paper integrates model results within solar spectrum, comparing results with a widely known radiative code SBDART (Ricchiazzi et al., 1998) and with ground measurements. Comparisons are made in clear atmosphere conditions in a rural environment (located at North East Brazil) and in turbid cloudless conditions induced by neighboring biomass burning (within Amazon region). In this context, published data from AERONET and SolRad-Net as well as MODIS monitoring suggest to be useful tools for this comparison.

2 METHOD

2.1 *Stochastic Model*

The two-flux method was applied in an atmosphere horizontally stratified in N= 16 layers, each one with optical thickness $\Delta\tau_i$ (i= 1, …, N), optical depth being $\tau_0 = 0$ at the top and τ_s at ground level. Propagation of radiation in the atmosphere is described using a stochastic model (Ceballos, 1988), where absorptance (A), transmittance (T) and reflectance (R) in a layer are interpreted as transition probabilities for propagation of diffuse photons, which were generated by the first interaction of direct photons impinging on the top of the atmosphere. It follows that diffuse radiative transfer can be described as a random walk of diffuse photons which finishes at absorption states located at ground, within atmospheric layers and (emerging) at the top of the atmosphere.

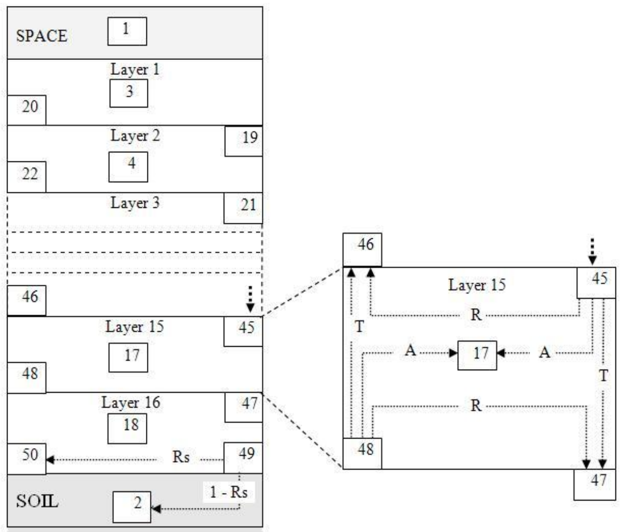

FIGURE 1. Structure of stochastic transitions

Figure 1 illustrates the propagation of diffuse radiation an atmosphere divided in 16 homogeneous layers. Generic transitions between states are shown by zooming layer 15. States 1 to 50 represent all situations eventually assumed by a diffuse photon. States 1 to 18 are absorbent states (sky, soil or layers 1, 2, 3, ... , 16) and the others are transitory states (even states for downwelling and uneven states for upward flux). It is seen that state 49 is a special one, since the following states of the radiation reaching that state are number 2 (absorption within ground, with probability 1 – Rs; Rs= surface reflectance) or 50 (reflexion with probability Rs). The random walk of the photons for the system Earth-atmosphere is described by a sequence of state vectors $\mathbf{P}_o$, $\mathbf{P}_1$, $\mathbf{P}_2$..., $\mathbf{P}_k$, … which follow a first-order Markov process, so that

$$\mathbf{P}_k = \mathbf{P}_o\,\mathbf{Q}^k, \quad \Pi(k) = \lim_{k\to\infty} P_k\,, \tag{1}$$

and $\mathbf{Q}$ is the Markov transition matrix. In equations (1), state vector $\mathbf{P}_o$ has dimension n = 3 x (N° of layers) + 2 and describes the distribution of probabilities for initial existence of diffuse photons in the n states, starting from incident direct photons in the top of the atmosphere; $\mathbf{P}_k$ is the state vector after k transitions, and Π is interpreted as the final probability state (transitory sates will have null probability).

Equations (1) refer to monochromatic radiation. Given N photons with frequency ν per second per unit area, impinging on the top of the atmosphere, $N.h\nu$ is the corresponding irradiance (h = Planck's constant). It is evident that Π(2) represents the fraction of energy that will be absorbed at ground, while $N\,h\nu$. Π(2) equals $G(\nu)/(1-Rs)$, $G(\nu)$ being global irradiance incident on ground. Finally, the global radiation the surface, G, in the interval of 0.3 to 3 μm can be estimated by integration over that interval:

$$G = \frac{\mu_0 E_o}{1 - Rs} \int_{0,3}^{3} S_0(\lambda)\Pi(\lambda)T_{H2O}(\lambda, w)d\lambda\,. \tag{2}$$

Here, So(λ) is spectral mean solar constant, E_0 is the correction factor for eccentricity of earth orbit (Iqbal, 1983), μ_0 is the cosine of the solar zenithal angle, Π is Π(2) according to Eq. (1), *Rs* is ground reflectance and T_{H2O} is the transmittance due to the water vapor in an atmosphere with precipitable water column *w*. It is to be noted that a spectrally averaged value is assumed for *R*s; also, equations (1) used in this paper do not account for water vapor absorption. Nevertheless this absorption happens mainly outside visible interval, where optical depth is low and therefore probability of ground absorption should be about 1-*R*s. Therefore, transmittance T_{H2O} may be introduced as a factor.

2.2 Model *Parameterizations*

It was adopted the tropical atmosphere profile of MacClatchey *et al*. (1971). The atmosphere with thickness of 100 km was divided in 16 layers as follows: 50 km for layer 1 (altitude between 50 and 100 km); 10 km for layers 2 and 3 (altitudes between 30 and 50 km); 6 km for layer 4 (altitude between 24 and 30 km), and 2 km for the layers 5, 6, ..., 16. To calculate the transmittance regarding H_2O and the optical thickness regarding O_3 it was used the parameterization of Leckner (1978). Leckner's values have been interpolated by continuous functions allowing for integration of Eq. (2) with spectral resolution $d\lambda$ = 0,005 μm.

Radiative properties *R*, *T*, *A* for each layer are estimated following a two-flux δ-SS approach for a mixture air+aerosol or air+ozone, that is a δ-approximation and hemispherical isotropy for diffuse radiation (Ceballos 1988 1989).

3 RESULTS OF TWO EXPERIMENTS

Two different situations were modeled for daily cycle of global irradiance and compared with local measurements of solar radiation: a rural site at Quixerê, North East Brazil (5,07 S; 37,86 W; 130 m height) on 16 September 2005, and a polluted atmosphere with burning biomass at Cuiabá, Brazilian Amazon region (15,739 S; 56,021 W; 210 m) on 6 September 2005.

Figures 2 and 3 resume the results. Their left sides, labeled with (a), show spectral downward irradiance as assessed by SBDART and by the stochastic model [ME], at the top of the atmosphere (Fi) and at ground level (FTr). Atmospheric parameters for Quixerê were measured or estimated *in situ* (atmospheric pressure = 970 hPa, ground reflectance, precipitable water, solar irradiance with a CNR1 pyranometer), or extracted from MODIS document MOD08: ozone load 270 DU, aerosol optical depth τ(055) = 0.12 and Angstrom coefficient α = 0.63. Due to lack of information, generic values were assumed for single scattering albedo (ω = 0.93) and asymmetry factor (g = 0.64). For Cuiabá site, solar radiation data were from SolRad-Net, while AERONET station provided pressure (P_o = 988 hPa), water vapor column (w = 3,26 $g.cm^{-2}$) and aerosol parameters τ(0.55) = 1.93, α = 1.87, ω = 0,94 and g = 0,58. Document MOD09 provided surface albedo Rs= 0.14 (for satellite passage at 1430 UT). In both cases, aerosol parameters were considered constant all along the diurnal period.

Figures (2a) and (3a) make evident that spectral characteristics described by both codes are essentially the same. However, average computational time using SBDART was about 10 seconds, while ME took only 2 seconds. Integration path in Eq. (2) was 0.005 μm.

Accuracy of each code may be discussed observing figures (2b) and (3b), which describe deviation related to local measurement of solar radiation. For the rural site (2b), from 12 UT until 17 UT (about 09 to 14 hours local time), deviations are +43.1 $W.m^{-2}$ for SBDART and +33.5 for ME, or about +5.0% and 3.9% of irradiance, respectively.

Global irradiance in the polluted atmosphere of Cuiabá, Figure (3b), exhibits better assessment for both codes. Deviation can oscillate between +15 an -30 $W.m^{-2}$ for SBDART, and between +28 and -20 $W.m^{-2}$ for ME. An averaged value of aerosol load values given by AERONET station was assumed, therefore it was constant during the day. In these conditions, accuracy of both codes oscillates between +4% and -3%. It is possible that such behavior could arise because aerosol load variability was not included. Errors associated to τ fluctuations were not included in this preliminary paper, but could lead to even better estimates of global radiation. For instance, note that deviations reported in Figure (2b) could diminish by at least 20 $W.m^{-2}$ if τ(0.55) increase to 0.2-0.25.

In addition, it seems evident a systematic difference of about +10 $W.m^{-2}$ between ME and SBDART results in both meteorological situations. This difference should be attributed to physical parameterizations of each code rather than to actual value of aerosol load.

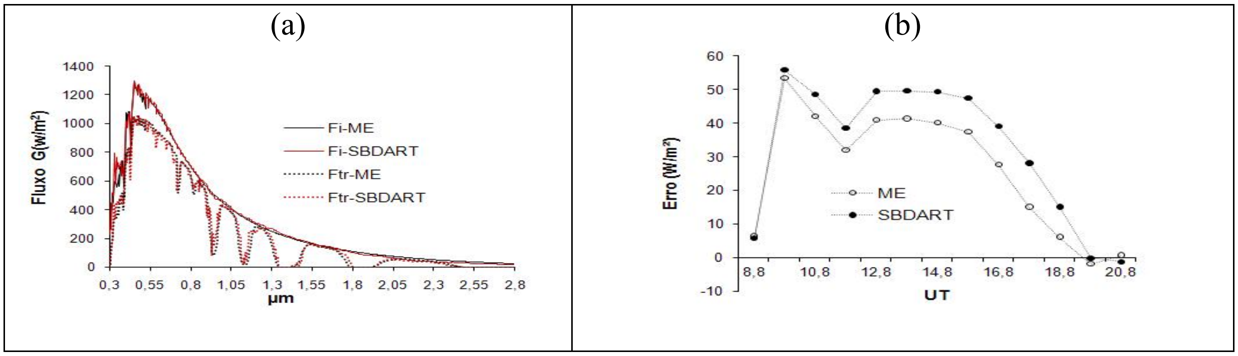

FIGURE 2. Quixerê, NorthEast Brazil, clear atmosphere. (a) Spectral fluxes calculated with the model (ME) and with SBDART (Fi: incident on top of atmosphere; Ftr: transmitted at ground level). Parameters: Rs= 0.15, aerosol load $\tau(0.55) = 0.12$, $\mu_o = 0.62$ and $w_{H2O} = 2.0$ g.cm^{-2}. (b) Daily cicles of deviation from measured global irradiance (UT: universal time).

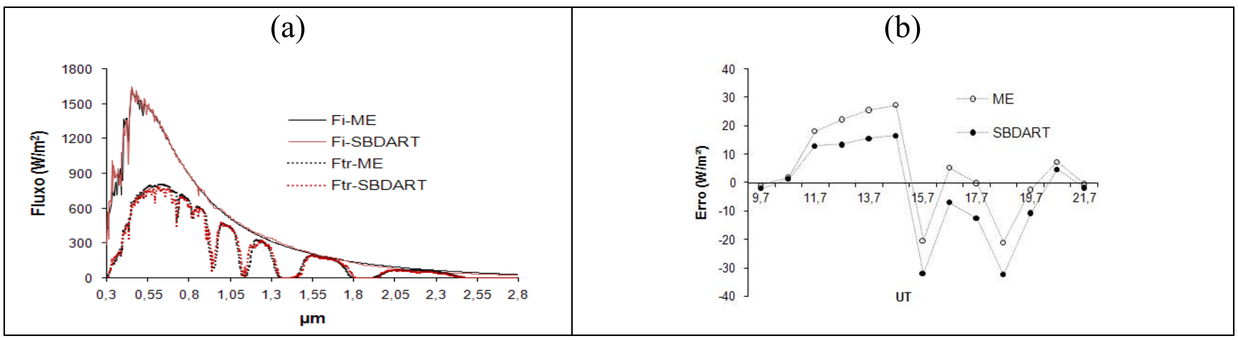

FIGURE 3. Cuiabá, Brazilian Amazon, turbid atmosphere due to burning biomass aerosol. (a) Spectral fluxes calculated with the model (ME) and with SBDART (Fi: incident on top of atmosphere; Ftr: transmitted at ground level). Parameters: aerosol load $\tau(0.55) = 1.93$, $\mu_o = 0.797$ and $w_{H2O} = 3.3$ g.cm^{-2}. (b) Daily cycles of deviation from measured global irradiance (UT: universal time).

4 CONCLUSIONS

The use of a stochastic model [ME] in a 16-layers stratified atmosphere describes efficiently the irradiance resulting of multiple scattering in a cloudless atmosphere. In the modeled cases (low and high aerosol load) ME model showed differences of +10 W.m^{-2} related to SBDART results; so it actually exhibits the same accuracy; however, it showed better performance related to computational cost (it is five times faster). The results suggest that description of optical properties of the atmosphere through continuous functions of the wavelength is an acceptable criterion. Some factors as aerosol parameterizations might contribute to the difference between SBDART and ME. Also, better definition of aerosol load variations during daytime could considerably reduce deviation related to "ground truth". Further numerical experiments validated with network measurements will be necessary for answering these questions and enhancing quality of model ME.

5 ACKNOWLEDGMENTS

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