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Approximate models for broken clouds in stochastic radiative transfer theory

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ABSTRACT

This paper presents approximate models in stochastic radiative transfer theory. The independent column approximation and its modified version with a solar source computed in a full three-dimensional atmosphere are formulated in a stochastic framework and for arbitrary cloud statistics. The nth-order stochastic models describing the independent column approximations are equivalent to the nth-order stochastic models for the original radiance fields in which the gradient vectors are neglected. Fast approximate models are further derived on the basis of zeroth-order stochastic models and the independent column approximation. The so-called “internal mixing” models assume a combination of the optical properties of the cloud and the clear sky, while the “external mixing” models assume a combination of the radiances corresponding to completely overcast and clear skies. A consistent treatment of internal and external mixing models is provided, and a new parameterization of the closure coefficient in the effective thickness approximation is given. An efficient computation of the closure coefficient for internal mixing models, using a previously derived vector stochastic model as a reference, is also presented. Equipped with appropriate look-up tables for the closure coefficient, these models can easily be integrated into operational trace gas retrieval systems that exploit absorption features in the near-IR solar spectrum.

1. Introduction

The accurate modeling of sub-pixel cloud inhomogeneities is one of the main problems in trace gas retrievals from nadir sounding instruments. The “cloud effects” increase when the spatial resolution increases (pixels become smaller) due to adjacency effects, or when the spatial resolution decreases (pixels become larger) due to nonlinearity (Jenses inequality) effects [1]. The new generation of European atmospheric composition sensors, like Sentinel 5 Precursor, Sentinel 4 and Sentinel 5 [2], requires fast and accurate radiative transfer models to properly account for cloud inhomogeneities.

The operational atmospheric retrieval algorithms are usually based on the independent column approximation, also known as the independent pixel approximation. To summarize the mathematical fundamentals of the models based on the independent column approximation, we consider a cloudy domain D and express the domain-average radiance at the top of the atmosphere $\langle I \rangle$ as

$$\langle I \rangle = \frac{1}{A}\int_S I(x,y)\,\mathrm{d}S, \tag{1}$$

where I is the radiance computed by a three-dimensional radiative transfer model and A is the area of the surface S bounding the domain D at the top of the atmosphere. Considering a discretization of the domain D in N discrete columns $D = \bigcup_{k=1}^{N} D_k$, yields $\langle I \rangle = \sum_{k=1}^{N} \nu_k \langle I_k \rangle$, with $\nu_k = A_k/A$ and $\langle I_k \rangle = (1/A_k)\int_{S_k} I(x,y)\,\mathrm{d}S$.

1. In the independent column approximation [3,4], the horizontal interaction between the columns is

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neglected, and the radiances $\langle I_k \rangle$ are approximated by the plane-parallel radiances $\mathcal{I}_k$, that is, $\langle I_k \rangle \approx \mathcal{I}_k$, giving $\langle I \rangle \approx (1/N)\sum_{k=1}^{N} \mathcal{I}_k$, for a uniform column division with $\nu_{1k} = 1/N$ for all k.

2. In the independent column approximation with modified source, developed by Gabriel and Evans [5], the direct solar beam is computed in a full three-dimensional atmosphere, and then used in an independent column diffuse radiative transfer model.
3. Other models based on the independent column approximation rely on the representation $\langle I \rangle \approx (1/N) \sum_{k=1}^{N} \mathcal{I}(\tau_k)$, where τ_k is the optical thickness of the column D_k. Assuming that τ_k are the realizations of a random variable τ, the sample mean representation of $\langle I \rangle$ translates into the integral representation

$$\langle I \rangle \approx \int_0^\infty \mathcal{I}(\tau) p(\tau)\, d\tau, \tag{2}$$

where $p(\tau)$ is a probability density function describing the variation of the optical thickness in D. In the gamma-weighted independent column approximation [6–8], τ is assumed to follow a gamma distribution. Otherwise, $p(\tau)$ can be approximated by a beta distribution or a lognormal distribution [15].
4. Proceeding with (2), the choice $p(\tau) = \delta(\tau - \overline{\tau})$, with $\overline{\tau}$ being the mean optical thickness in D, gives $\langle I \rangle \approx \mathcal{I}(\overline{\tau})$. Several models, based on simple rescaling of the mean optical thickness $\overline{\tau}$, have attempted to improve this approximation. In the effective thickness approximation [3], the representation $\langle I \rangle \approx \mathcal{I}(\eta\overline{\tau})$ has been used for marine stratocumulus layers, while in the co-packing exponent model [9,10], the choice $\langle I \rangle \approx \mathcal{I}(\overline{\tau}^{\alpha})$ has been proposed for more strongly variablemedia. Specifically, Cahalan et al. [3] used self-affine fractal functions to describe the internal variability of geometrically plane-parallel clouds, while Gabriel et al. [9] and Davis et al. [10] used self-similar fractal sets to describe the extreme geometrical variability of their media. Moreover, in the equivalent homogeneous cloud approximation [11,12], the effective thickness approximation has been generalized to account for averaging-scale and solar zenith-angle effects. Computationally speaking, these methods capture in a statistical sense the unresolved spatial variability effects by performing a single one-dimensional radiative transfer computation with effective optical parameters. Similar approaches, also known as "homogenization" approaches, are the closure scheme for the fluctuations of the radiance field proposed by Stephens [13], and the renormalization theory elaborated by Cairns et al. [14].
5. For broken clouds described by a binary statistical mixture, the probability density function in (2) is chosen as $p(\tau) = A_c\delta(\tau - \tau_1) + (1 - A_c)\delta(\tau - \tau_0)$, where τ_1 and τ_0 are the optical thicknesses in the cloud and in the clear sky, respectively, and A_c is the cloud fraction. In this case, we are led to the linear mixing model

$$\langle I \rangle \approx A_c \mathcal{I}(\tau_1) + (1 - A_c)\mathcal{I}(\tau_0), \tag{3}$$

which represents the major simplification of the independent column approximation. For an exhaustive analysis of approximate models in atmospheric three-dimensional radiative transfer we refer to [15,16].

Another class of methods for computing the domain-average radiance belongs to stochastic radiative transfer theory. Cloud fields can be regarded as stochastic scattering media due to their internal inhomogeneity and stochastic geometry. The radiative transfer through these media can be described by stochastic radiative transfer models, in which new transport equations, relating the statistical parameters of the clouds to those of the radiance field, are derived. The main assumption for computing the domain-average radiance is the ergodic assumption, according to which, the domain-average radiance is approximated by the ensemble-average radiance. For trace gas retrievals, this method is especially attractive when no information about the spatial distribution of the cloud fields is available. The stochastic radiative transfer theory, in which the three-dimensional radiative transfer in broken clouds has been cast as two coupled integro-differential equations, one for the mean radiance in the cloud, and the other for the mean radiance in the clear sky, includes works dating at least to the seminal paper by Avaste and Vainikko [17] and analyzing the influence of the stochastic cloud geometry on radiative transfer [18–26]. A more recent and completely different approach to stochastic radiative transfer theory, using new transport equations based on non-exponential propagation kernels, has been described in [27,28]. In [29] we derived a first order-stochastic model for broken cloud fields, which requires the solution of a vector radiative transfer equation involving the mean radiance field and the covariance of the fluctuations of the radiance field and the indicator field. Although accurate, this vector stochastic model cannot be used for operational trace gas retrievals because it is computationally expensive. For this reason, we focus on the derivation of fast and sufficiently accurate approximate models on the basis of zeroth-order stochastic models and the independent column approximation.

Our paper is organized as follows. After formulating the problem in Section 2, we present nth-order stochastic models for the diffuse and total radiances in Section 3. The independent column approximation and its modified version with a solar source computed in a full three-dimensional atmosphere are formulated in a stochastic framework and for arbitrary cloud statistics in Section 4. A first class of fast homogenization approaches, the so-called internal mixing models are introduced in Section 5 by considering zeroth-order stochastic models and by imposing appropriate closure relations on the first-order covariance terms. A general technique for deriving approximate models on the basis of the independent column approximation is described in Section 6. This technique will enable us to give a new interpretation of internal mixing models, and to introduce external mixing models for broken cloud fields. The accuracy of the mixing models is analyzed in Section 7 by using the Spherical Harmonics Discrete Ordinate Method (SHDOM) [30] as a reference. The final section of our paper contains a few concluding remarks.

2. Problem formulation

We consider an atmosphere consisting of air molecules and clouds and denote by $\sigma_{\mathrm{ext}}^{0,1}$, $\sigma_{\mathrm{sct}}^{0,1}$ and $P_{0,1}$ the extinction