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Representation of the photon pathlength distribution in a cloudy atmosphere using finite elements

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Abstract

A new method to derive the photon pathlength probability density function with respect to the photon geometrical path (PDF-GP) is proposed in this paper. This method is based on a finite elements fit of the true PDF-GP using a step function with equidistant intervals. The new method is evaluated based on reference PDF-GPs derived via Monte-Carlo radiative transfer simulations for different single and multilayer clouds with and without surface albedo. The finite elements method was found to perform better than classical Laplace inversion techniques. For the case of two-layer clouds with a thin cirrus cloud (optical thickness 0.5) above a low-level cloud, it is shown that the finite elements method is able to separate the contribution of both cloud layers to the total radiance and, in principle, allows to simultaneously infer cloud top heights of both cloud layers given that enough independent radiance observations at different gas absorption optical depths are taken.

Keywords: Photon path length; Multiple scattering; Solar radiation

1. Introduction

Multiple scattering and absorption of sunlight by clouds are processes that contribute to the atmosphere's diabatic heating. Yet, our current understanding of the interaction between

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scattering and absorption in cloudy atmospheres is limited, resulting in large uncertainties for example in modeling radiative heating rates that are needed in global circulation models.

While global circulation models need fast broadband radiative transfer schemes, fundamental studies on scattering absorption interaction can best be performed using spectrally highly resolving measurements and simulations. Several authors have proposed the oxygen-A absorption band around 763 nm to derive cloud properties and to study scattering absorption interaction in cloudy atmospheres [1–4]. The advantage of using the oxygen-A band is that oxygen is well mixed up to very high altitudes. Furthermore, the absorption coefficient of oxygen in the A band varies over approximately seven orders of magnitude within a comparatively small spectral interval, so that cloud optical parameters can be treated as independent of wavelength and, at the same time, different absorption depths can be scanned given an instrument with sufficient spectral resolution.

Pioneering work in measuring absorption spectra, deriving average photon pathlength, and modeling the PDF-GP has been done in the 1970s by Dianov-Klokov et al. [5], Dianov-Klokov and Krasnokutskaya [6], Gechko et al. [7] and others. A review on these papers can be found in Feigelson [8]. Dianov-Klokov et al. [9] used a Monte-Carlo model to derive the pathlength distribution of photons for different homogeneous and layered clouds and found a strong variability of the PDF-GP dependent on the vertical structure of the cloud and on surface albedo.

The PDF-GP also provides a convenient way to describe the absorption scattering interaction theoretically. Via the principle of equivalence [10], the observed radiance at any absorption channel can be inferred from an absorption-free channel and the gas volume absorption coefficient, given that the PDF-GP is known. Reversely, Bakan and Quenzel [11], Pfeilsticker et al. [3], Heidinger and Stephens [4], Min and Harrison [12], Min et al. [13], and Preusker [14] use an inverse Laplace transformation to derive the PDF-GP from a set of spectrally highly resolving observations in the oxygen-A band. While several authors define the probability density function for the geometrical path (PDF-GP) of the photons Pfeilsticker et al. [3], other authors derive the probability density function of the optical path of the photons in the scattering medium (PDF-OP, [4]). The advantage of the latter is that it directly relates to the optical properties of the scattering medium. However, if the scattering medium is not uniformly distributed as in the case of multi-layer clouds, the PDF-OP does not account for the light path between the scattering layers (see for example Heidinger and Stephens [15]). A common feature of all PDF's derived via Laplace transform is that they are mathematically under-determined [3,14], so that assumptions about the shape of the PDF must be made. Many authors use a single Gamma function to approximate the Laplace transform of the PDF-GP. Bakan and Quenzel [11] show that in the case of non-negligible surface albedo the PDF-GP might not be well approximated by a single Gamma function. This finding is strongly supported by the features reported for 'measured' PDF-GPs by Dianov-Klokov et al. [9]. While several authors point to the limitations of using a single Laplace transform for multi-layer cloud systems [11,16,3] of observed spectra to derive the photon pathlength distribution, its accuracy has, to our knowledge, not been proven against Monte-Carlo simulated PDF-GPs as introduced by Dianov-Klokov et al. [9].

In recent years, photon pathlength distributions have become increasingly important, triggered firstly by the availability of spectrally more highly resolving observations of narrow absorption features (e.g. Pfeilsticker et al. [3]) and secondly, by an increased knowledge about the relation between cloud microphysical (e.g. Brenguier et al. [17]) and macrophysical (e.g. Marshak et al. [16]) properties and their radiative characteristics.