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An efficient approach to estimate the transmittance and reflectance of a mixture of aerosol components

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ABSTRACT

Atmospheric aerosols are formed by a mixture of different chemical components that changes rapidly with time and space. The refined characterization of this mixture is crucial to meet the accuracy requirements of satellite products derived from passive sensor data in the shortwave wavelengths. This article proposes an efficient analytical approach to estimate two key radiative terms in aerosol remote sensing: the transmittance and reflectance of an aerosol mixture. This study demonstrates that these terms can be approximated by a simple weighted average of the individual radiative counterparts related to each aerosol component. Weights are the optical depths resulting from each aerosol component separately. The proposed approach is very fast and is exact for the first order of scattering. Its accuracy is assessed against exact radiative transfer calculations for a broad range of aerosol scenarios. For typical aerosol conditions (optical depth lower than 1.0 and solar zenith angle lower than 70°), the average error of estimated transmittances is 0.6%. Reflectances are affected by a higher average error of 7.6% due to their higher sensitivity to multiple scattering orders. The proposed approach may advantageously replace the use of sophisticated radiative transfer codes at the cost of a slight accuracy decrease to better answer the needs of the near real time constraint required by the remote sensing community.

1. Introduction

Terrestrial aerosols are a mixture of different aerosol components found in the troposphere (Koepke et al., 1997). Each aerosol component is representative for atmospheric chemical substances resulting from similar sources or processes. The composition of aerosol mixtures greatly varies with time and space (Dubovik et al., 2002; Aaltonen et al., 2012). In this context, default aerosol types are defined to embrace the wide range of existing aerosol mixtures on Earth. The optical properties of these predefined types (and of the forming components) are available by means of some databases (Levoni et al., 1997; Hess et al., 1998). Nevertheless, some aerosol scenarios are still ignored or misrepresented by the existing types. For example, the mixing ratio of aerosol components in real aerosol mixtures may not match the values used in the default types (Dubovik et al., 2002). Also, mixtures of different aerosol types are usual. For example, continental and desertic aerosols exist simultaneously over Europe in the summertime when Saharan dust is transported northward (Israelevich et al., 2012). A similar scenario occurs over coastal regions where sea salt is blown inland (Tsyro et al., 2011). Under these circumstances, the optical properties of the aerosol layer are not directly accessible.

Total extinction of solar irradiance due to aerosol particles accounts for 10–20% for zero zenith angle (Psiloglou et al., 1997). In this context, remote sensing techniques benefit from the modeling of the radiative effects due to aerosol extinction. This is the case of algorithms aimed at estimating

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radiative quantities in the shortwave at the surface level (Geiger et al., 2008; Li et al., 2013; Ceamanos et al., 2013), of atmospheric constituents (Swartz et al., 2005), or related to aerosol particles themselves (Carrer et al., 2010; Lyapustin et al., 2011; Dubovik et al., 2011). In these techniques, aerosol effects are generally characterized by their transmittance and reflectance terms. For instance, aerosol reflectance is crucial to estimate the multiple scattering between the surface and the atmosphere layer (Geiger et al., 2008). Also, the transmittance of aerosols must be accounted for to estimate accurately radiative fluxes at the surface level (Gueymard, 2003). These two key radiative terms can be computed for known aerosol components or default aerosol types using suitable parameterizations (Kokhanovsky et al., 2005) or radiative transfer codes coupled with appropriate optical properties (Mayer & Kylling, 2005). Nonetheless, this task becomes more difficult in the presence of aerosol mixtures that are not represented by default aerosol types. Although some atmospheric radiative transfer codes are able to account for any mixture of known aerosol components, following such an option is hard to envisage in an operational system due to its high computational cost. In this case, the dominant default aerosol type is commonly retained (Geiger et al., 2008; Carrer et al., 2010). However, the consideration of an inaccurate aerosol type can introduce significant bias affecting the radiative terms provided by remote sensing techniques (Boucher & Anderson, 2005; Kahn et al., 2005).

In this article, we present an efficient analytical approach to estimate the transmittance and reflectance of an aerosol mixture based on the individual radiative counterparts of the forming aerosol components. Based on a simplification of the atmospheric radiative transfer, this study demonstrates that this can be achieved by a simple weighted average. In particular, weights are the individual optical depths resulting from each aerosol component separately. The proposed approach is very fast and is exact for the first order of scattering.

This article is organized as follows. First, the approach to estimate the transmittance and reflectance of an aerosol mixture is presented in Section 2. The validity of the proposed approach, especially in front of multiple scattering, is evaluated for a large range of situations in Section 3. Performances and limitations are discussed in Section 4. Eventually, conclusions are drawn in Section 5.

2. Deriving the transmittance and reflectance of a mixture of different aerosol components

The following developments aim at deriving the transmittance and reflectance of an aerosol mixture based on two main concepts. For that purpose, we consider a gas-free plane-parallel atmosphere made by an aerosol layer composed of q different components. Aerosol particles are assumed to be spherical and homogeneously distributed along the vertical. The total amount of particles is set by the total aerosol optical depth (AOD or τ_0) at the lower boundary of the aerosol layer. Each aerosol component $i = \{1 \ldots j \ldots q\}$ is related to an individual optical depth ($\tau_{0,i}$), where $\tau_0 = \sum_{\forall i} \tau_{0,i}$. The incidence and observation directions are determined by the cosine of the solar zenith angle ($\mu_0 = \cos\theta_0$), the cosine of the view zenith angle ($\mu = \cos\theta$), and the scattering angle (ξ).

2.1. Transmittance and reflectance of a homogeneous aerosol layer

The downward global transmittance (t) and reflectance (r) of an aerosol layer are defined as

$$t(\mu_0, \mu, \xi) = \frac{\pi I_\downarrow(\mu_0, \mu, \xi)}{\mu_0 E_0}, \tag{1}$$

$$r(\mu_0, \mu, \xi) = \frac{\pi I_\uparrow(\mu_0, \mu, \xi)}{\mu_0 E_0}, \tag{2}$$

where $I_\uparrow$ and $I_\downarrow$ are the upwelling and downwelling intensities, respectively. The incident light flux is represented by E_0.

Photons penetrating into an aerosol layer are scattered in all directions. In order to simplify the scattering process, the total intrinsic scattering function can be decomposed into the successive order of scattering (Hansen & Travis, 1974). The basic principle is that the total transmitted and reflected intensities can be expressed as the sum of the individual intensities resulting from photons scattered once, twice, three times, etc. Hence, transmittance and reflectance can be expressed using a similar decomposition such as

$$t = \sum_{p=1}^{\infty} t_n = t_{SS} + t_{MS}, \tag{3}$$

$$r = \sum_{p=1}^{\infty} r_n = r_{SS} + r_{MS}, \tag{4}$$

where p stands for the order of scattering and subscripts SS and MS refer to single scattering ($p = 1$) and multiple scattering ($p = [2 \ldots \infty]$), respectively.

In this study, we characterize the aerosol layer using the widely used single scattering approximation. Therefore, the transmittance and reflectance of the total aerosol layer are approximated as the first order transmittance (t_{SS}) and reflectance (r_{SS}) functions (Hansen & Travis, 1974; Kokhanovsky, 2008) as

$$t(\mu_0, \mu, \xi) \simeq t_{SS}(\mu_0, \mu, \xi) = \frac{\omega_0 p(\xi)}{4(\mu_0 - \mu)} \left(e^{-\tau_0/\mu_0} - e^{-\tau_0/\mu}\right), \tag{5}$$

$$r(\mu_0, \mu, \xi) \simeq r_{SS}(\mu_0, \mu, \xi) = \frac{\omega_0 p(\xi)}{4(\mu_0 + \mu)} \left(1 - e^{-\tau_0(1/\mu_0 + 1/\mu)}\right), \tag{6}$$

where ω_0 is the single scattering albedo and $p(\xi)$ is the scattering phase function. The latter parameter is typically modeled as a function of the asymmetry factor g.

The single scattering approximation is well known in atmospheric radiative transfer as it is used, for example, as a building block in a number of exact techniques for the solution of radiative transfer equation (van de Hulst, 1980). In this study, the single scattering approximation will allow us to derive appropriate and simple functions for the reflectance and transmittance of a mixture of different aerosol species. However, it must be noticed that this approximation does not