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Coefficients of an analytical aerosol forcing equation determined with a Monte-Carlo radiation model

Taufiq Hassan [a], H. Moosmüller [b], Chul E. Chung [b,*]

[a] WISE (Weather Information Service Engine) Institute, Hankuk University of Foreign Studies, Korea
[b] Desert Research Institute, 2215 Raggio Parkway, Reno, NV 89512, USA

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ABSTRACT

Simple analytical equations for global-average direct aerosol radiative forcing are useful to quickly estimate aerosol forcing changes as function of key atmosphere, surface and aerosol parameters. The surface and atmosphere parameters in these analytical equations are the globally uniform atmospheric transmittance and surface albedo, and have so far been estimated from simplified observations under untested assumptions. In the present study, we take the state-of-the-art analytical equation and write the aerosol forcing as a linear function of the single scattering albedo (SSA) and replace the average upscatter fraction with the asymmetry parameter (ASY). Then we determine the surface and atmosphere parameter values of this equation using the output from the global MACR (Monte-Carlo Aerosol Cloud Radiation) model, as well as testing the validity of the equation. The MACR model incorporated spatio-temporally varying observations for surface albedo, cloud optical depth, water vapor, stratosphere column ozone, etc., instead of assuming as in the analytical equation that the atmosphere and surface parameters are globally uniform, and should thus be viewed as providing realistic radiation simulations.

The modified analytical equation needs globally uniform aerosol parameters that consist of AOD (Aerosol Optical Depth), SSA, and ASY. The MACR model is run here with the same globally uniform aerosol parameters. The MACR model is also run without cloud to test the cloud effect. In both cloudy and cloud-free runs, the equation fits in the model output well whether SSA or ASY varies. This means the equation is an excellent approximation for the atmospheric radiation. On the other hand, the determined parameter values are somewhat realistic for the cloud-free runs but unrealistic for the cloudy runs. The global atmospheric transmittance, one of the determined parameters, is found to be around 0.74 in case of the cloud-free conditions and around 1.03 with cloud. The surface albedo, another determined parameter, is found to be around 0.18 and 0.28 in case of cloud-free and cloudy-sky conditions respectively. Because the cloudy-sky runs yield unrealistic parameter values, we conclude that the equation is more adequate for cloud-free conditions.

1. Introduction

Aerosols affect climate in multiple ways. The effect of aerosols on climate is normally quantified in terms of aerosol radiative forcing. Direct aerosol radiative forcing is

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[*] Corresponding author.
E-mail address: Eddy.Chung@dri.edu (C.E. Chung).

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due to aerosol scattering and absorption of solar radiation [1]. Aerosol radiative forcing is defined as the effect of anthropogenic aerosols (or aerosol change in time) on the radiative fluxes at the top of the atmosphere (TOA) and at the surface and on the absorption of radiation within the atmosphere. The effect of the total (anthropogenic+natural) aerosols is called aerosol radiative effect or total aerosol forcing.

The magnitude of the global aerosol direct radiative forcing has been estimated to range from -0.85 to $+0.15\,\mathrm{W\,m^{-2}}$ in the 5th IPCC report [2]. This range of estimate is based on estimates from multiple approaches. The most common approach is a model-based approach of simulating global aerosol amount, distribution, and characteristics, and processing the predicted global aerosol distribution by a radiation model [3]. Aerosol observations provide an alternative estimate of aerosol radiative forcing. Attempts have been made to constrain global aerosol simulations by observations [4–7]. This can be referred to as a semi-empirical approach. In a purely observational approach, measured relationships between aerosol amount and TOA radiative flux allow one to bypass even a radiation model [8]. Purely observational methods, however, have been limited primarily to assessing the direct aerosol radiative effect (i.e., natural + anthropogenic aerosol forcing) under clear sky conditions.

Although not used for the IPCC report aerosol forcing estimates, simple analytical solutions have been used for estimating the direct effect of aerosols on the radiation budget [9–11]. Because of their simplicity, these equations can be very useful in explaining the explicit dependence on individual parameters determining the forcing [11]. These explicit relationships are useful in understanding the influence of microphysics and optics on aerosol radiative forcing.

In the present study, we validate the state-of-the-art analytical equation by Chýlek and Wong [11] with the radiation output from one of the most realistic aerosol forcing simulation models, that is the Monte-Carlo Aerosol Cloud Radiation (MACR) model as in Choi and Chung [12]. This model was originally developed during INDOEX [13] and enhanced by Chung et al. [5] and Choi and Chung [12]. This model, which accounts for multi-layer clouds from satellite observations, has undergone comprehensive validation of the simulated fluxes at the TOA and at the surface over 100 land and island stations (agreement with observations is within a few $\mathrm{W\,m^{-2}}$) [14]. Satellites normally cannot detect multi-layer clouds, and, as a result, the presence of low-level cloud is derived normally in the absence of overlying clouds. To construct multi-layer clouds, a random overlap scheme [14] was incorporated into the MACR model [5]. Only shortwave (i.e., solar) radiation is considered.

This paper is structured as follows. Section 2 introduces the analytical equation, the radiation model, and the method for calculating the parameters in order to verify the equation. Section 3 displays and explains the results. Here, we discuss and compare our results too. The summary follows in Section 4.

2. Analytical equation

Charlson et al. [10] developed a simple equation for quantifying the direct global-average radiative forcing by sulfate aerosols. This equation included only the effect of non-absorbing aerosols such as sulfate. Some aerosols such as black and brown carbon and mineral dust can absorb sunlight significantly [1,15]. To address absorbing aerosols, Chýlek and Wong [11] extended the equation from Charlson et al. [9]. Their equation is valid for purely-scattering and also for absorbing aerosols and is currently the state-of-the-art analytical equation for direct aerosol forcing.

The original equation by Chýlek and Wong [11] is as follows.

$$\Delta F_{\mathrm{aer}} = -\frac{S_0}{4}T_{\mathrm{atm}}^2(1-A_{\mathrm{cld}})\left[2\overline{\beta}\tau_{\mathrm{scat}}(1-R_{\mathrm{surf}})^2-4\tau_{\mathrm{abs}}R_{\mathrm{surf}}\right], \tag{1}$$

where ΔF_{aer} is aerosol forcing, S_0 the solar constant, T_{atm} the transmittance of the atmosphere above the aerosol layer, A_{cld} the cloud fraction, R_{surf} the surface albedo, $\overline{\beta}$ the fraction of radiation that is scattered back to the upper hemisphere (referred to here as the average upscatter fraction), τ_{scat} the aerosol layer scattering optical depth and τ_{abs} the aerosol layer absorption optical depth.

In the present study, we first modify the form of this equation to replace aerosol scattering and absorption optical depths with SSA (single scattering albedo) ω and the aerosol optical depth (AOD) τ, and give the aerosol forcing efficiency $\Delta F_{\mathrm{aer}}/\tau$ as

$$\frac{\Delta F_{\mathrm{aer}}}{\tau} = -\frac{S_0}{2}T_{\mathrm{atm}}^2(1-A_{\mathrm{cld}})\left[\overline{\beta}\omega(1-R_{\mathrm{surf}})^2-2(1-\omega)R_{\mathrm{surf}}\right] \tag{2}$$

The aerosol forcing efficiency (i.e., aerosol radiative forcing per aerosol optical depth) given in Eq. (2) depends on two intrinsic aerosol properties: ω and $\overline{\beta}$. It should be noted that the analytical equation assumes values for parameters and coefficients, such as AOD and the average upscatter fraction, to be uniform or averaged over the sunlit hemisphere of the earth. Also, Eq. (2) implies a linear relationship between aerosol forcing and SSA. In the present study, we will test this implied relationship using the MACR model output. We will also determine the atmospheric transmittance and surface albedo in the equation using the MACR model, to see if the previously adopted values need to be revised substantially.

2.1. The upscatter fraction

The upscatter fraction is a function of the solar zenith angle θ_0 and is denoted as $\beta(\theta_0)$. Eq. (2) utilizes the average upscatter fraction $\overline{\beta}$, which is the fraction of radiation that is scattered back to the space for the entire sunlit hemisphere. Thus, the average upscatter fraction $\overline{\beta}$ is no longer a function of the solar zenith angle and is only a function of aerosol optics. In order to estimate aerosol radiative