Journal of Quantitative Spectroscopy & Radiative Transfer 219 (2018) 292–303

Contents lists available at ScienceDirect

Journal of Quantitative Spectroscopy & Radiative Transfer

journal homepage: www.elsevier.com/locate/jqsrt

Sensitivity of dust radiative forcing to representation of aerosol size distribution in radiative transfer model

Yiran Peng[a], Jian-Qi Zhao[b], Zhian Sun[c], Wenjie Zhao[a], Xiaodong Wei[d], Jiangnan Li[e,*]

[a] *Department of Earth Science, Tsinghua University, Beijing 100081, China*
[b] *Institute of Atmospheric Physics, Beijing 100081, China*
[c] *Australian Bureau of Meterology, Melbourne, Australia*
[d] *Meteorological Center, East China Bureau of Air Control, Shanghai, China*
[e] *Canadian Center for Climate Modeling and Analysis, University of Victoria, Victoria, British Columbia, Canada*

ARTICLE INFO

Article history:
Received 14 February 2018
Revised 26 March 2018
Accepted 5 April 2018
Available online 4 August 2018

Keywords:
Dust aerosol
Size distribution
Radiative forcing
GCM Simulation

ABSTRACT

Dust size distributions from the two-mode scheme and the continuous scheme are compared with AERONET observations. The two-mode dust scheme contains fine and coarse modes with fixed effective radius and effective variance for each mode. The continuous scheme takes into account the size distribution with a prognostic variation of effective radius and effective variance. The size distribution of the two-mode scheme changes with the fine/coarse mode mass ratio. However, it is impossible to make both effective radius and effective variance to match with the observed result by adjusting the fine/coarse mode mass ratio. The size distribution from the continuous scheme can be much closer to the observations.

A new parameterization for dust optical properties is proposed based on the continuous scheme. The shape of non-spherical dust particles is approximated using a rotational symmetric spheroid in optical property calculations. This parameterization can also be used for the two-mode scheme.

The parameterization is applied to a set of idealized one-dimensional radiative transfer calculations to investigate the sensitivity of dust radiative forcing to various attributes, including dust loading, dust solar heating rate, surface albedo, effective radius and variance. The parameterization is also evaluated in a climate model. Though at each selected region the two-mode scheme can always be tuned to approximate the results of the continuous scheme, on global scales, however, the two-mode dust scheme cannot produce similar radiative forcing as the continuous scheme and the relative error can be over 30% in several desert regions. The accurate results in radiative forcing can not be achieved by tuning the mass ratio.

1. Introduction

Anthropogenic and natural aerosols are recognized as significant atmospheric constituents influencing the climate system. Among all kinds of aerosols, the mineral dust has its distinctive characteristics. 1, the geological distribution of mineral dust is very uneven with significant emission sources in Northern Hemisphere (e.g., Saharan desert and eastern Asian desert). Thus the regional energy balance is strongly affected. The direct radiative forcing by mineral dust can be much larger than other aerosols in the continent (e.g., Fig. 3 in [1]). 2, Increasing amount of mineral dust can change the surface albedo with excessive deposition on ice and snow [2,3], which is one of the possible reasons for the acceleration of melting sea ice in Polar region. 3, mineral dust aerosol favors the formation of ice crystals [4] because of its shape and insolubility. Ice particles in the cloud have a potential effect on precipitation and can modulate the hydrological cycle. 4, unlike most of the other aerosols, the hygroscopic effect of soil dust is very weak [5]. Choobari et al. [6] reviews on dust physical property and dust impact on the climate system and cloud properties.

Many observations have suggested that dust aerosol size distribution behaves differently in world-wide source regions (e.g., [7,8]). A dust size spectrum usually exhibits a wide range of values through source and sink processes. For example, gravitational settling removes large size particles near dust source, and wet deposition tends to wash out small particles in and below clouds. In most of GCMs, a size-resolved scheme is expected to simulate the size distribution of the dust aerosol in a prognostic way (e.g., [9–11]). However, dust has been simply treated in the radiative

* Corresponding author.
E-mail address: jiangnan.li@canada.ca (J. Li).

https://doi.org/10.1016/j.jqsrt.2018.04.037
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calculation of some climate models, which uses a two-mode scheme that assumes prescribed log-normal distribution in two categories for fine and coarse modes. Each mode is defined with fixed effective radius, r_{eff} and effective variance, v_{eff}, while dust aerosol mass in each mode is prognostic (e.g., [12,13]).

In [14] the dust size distribution has been investigated based on the selected 24 'dusty' sites from AERONET (Aerosol Robotic Network) inversion retrieval data. The dust size distribution varies with location and time, which is shown in the change of r_{eff} and v_{eff}. To simulate the dust size distribution, the assumed log-normal or Gamma size distributions are used, by adopting the same values of r_{eff} and v_{eff} from observations. However, it is found in [14], though with the same pair of r_{eff} and v_{eff}, the two assumed aerosol size distributions can still be very different from the observed results. The skewness is another important value to judge how close the assumed size distribution is to the observed result. The skewness value of the Gamma size distribution is always much closer to the observed result, by comparing with that of the log-normal size distribution. Therefore the parameterization for dust optical property based on the Gamma size distribution can produce accurate results of dust radiative forcing against the benchmark calculation [14]. The Gamma function can be used in two manners, the first one with the pair of r_{eff} and v_{eff} being predicted by model and the second one with fixed r_{eff} and v_{eff}. The second one is widely used in GCMs. We define the first one as the continuous scheme because the prognostic r_{eff} and v_{eff} vary continuously, and the second one as the two-mode scheme.

This work is a continuous study of Li et al. [14] for following three aspects: 1. The parameterization of dust optical properties using a continuous scheme, which takes full-size information about the prognostic dust size distribution, has been introduced in [14]. However, dust optical properties were calculated by Mie scattering method and this has to be improved by including the effect of non-spherical dust particles. 2. The two-mode scheme for dust size distribution, which is widely used in GCMs, needs a systematic evaluation by comparing with the AERONET observations and the continuous scheme. 3. Investigating of the sensitivity of dust radiative forcing to different parameters in order to understand the physical characteristics of dust for radiation.

In Section 2, the dust size distribution is investigated by comparing with the retrieved result from the AERONET observations. The parameterization of dust optical properties is given in Section 3. To understand dust radiative forcing and its sensitivity to the two-mode and continuous schemes, the aforementioned parameterization is implemented into a one-dimensional radiative transfer model. Results are analyzed in Section 4 according to changes in dust loading, surface albedo, and effective radius and variance. GCM simulations of dust radiative forcing by comparing of the continuous scheme and two-mode scheme are shown in Section 5. Finally, concluding remarks and discussions are presented in Section 6.

2. Dust aerosol size distribution

Size distribution of aerosol can be well expressed [15]:

$$n(r) = \frac{dN}{dr} = \frac{1}{4/3\pi r^4}\frac{dV}{dlog(r)} \tag{1}$$

where r is the radius for spherical particle. For non-spherical particles, r denotes the volume-equivalent radius $r = (3V/4\pi)^{1/3}$ [16]. N is the aerosol number concentration. V is the aerosol volume concentration. The size distribution can be characterized by two parameters of effective radius r_{eff} and effective variance v_{eff}, which are defined as:

$$r_{eff} = \frac{\int r^3 n(r)\,dr}{\int r^2 n(r)\,dr} = \frac{m_3}{m_2} \quad \text{and} \quad v_{eff} = \frac{\int (r - r_{eff})^2 r^2 n(r)\,dr}{r_{eff}^2 \int r^2 n(r)\,dr} = \frac{m_4 m_2}{m_3} - 1$$

where the moment defined as $m_i = \int r^i n(r)\,dr$ [14]. Known $n(r)$, r_{eff} and v_{eff} can be obtained.

Global scale observations show that the size distribution of mineral dust aerosol exhibits multiple modal patterns. The data of aerosol volume-size distributions near the surface at "dusty" sites are available from AERONET inversion retrieval program. "Dusty" sites are defined in [17], where the monthly mean aerosol optical depth (AOD) is relatively high and dominated by large size particles in the continent. In [14] the aerosol size distributions in 24 "dusty" sites from AERONET were shown for both annual mean and monthly mean. The plots of [14] showed different patterns of size distribution in different dust source regions (indicated with different values of r_{eff} and v_{eff} in each site).

Usually the aerosol size distribution is assumed to closely resemble the log-normal distribution as

$$n(r) = \frac{dN}{dr} = \frac{N_0}{\sqrt{2\pi}\, r \ln\sigma} \exp\left(-\frac{(\ln r - \ln r_0)^2}{2(\ln\sigma)^2}\right), \tag{2}$$

In Eq. (2), N_0 is the total number density, r_0 is the geometric mean radius (for the mode) and σ is the geometric standard deviation. $r_{eff} = \frac{m_3}{m_2} = r_0 \exp(2.5(\ln\sigma)^2)$ and $v_{eff} = \frac{m_2 m_4}{m_3^2} - 1 = \exp((\ln\sigma)^2) - 1$. Thus r_0 and σ are determined by r_{eff} and v_{eff}. The Gamma size distribution is also commonly used to resemble the particle size distribution.

$$n(r) = \frac{dN}{dr} = N_0 \frac{\beta^{\alpha+1}}{\Gamma(\alpha+1)} r^{\alpha} e^{-\beta r} \tag{3}$$

where Γ is the Gamma function, α and β are constant coefficients with relationship to the effective radius and variance as $r_{eff} = \frac{m_3}{m_2} = (\alpha+3)/\beta$ and $v_{eff} = \frac{m_2 m_4}{m_3^2} - 1 = 1/(\alpha+3)$.

In the bulk aerosol scheme, the detailed size distribution cannot be resolved. A two-mode scheme is used, which contains a fine mode ($r_{eff} = 0.39, v_{eff} = 0.597$) and a coarse mode ($r_{eff} = 1.9, v_{eff} = 0.61$) [18]. Assume the fine and coarse modes size distributions are $n_f(r)$ and $n_c(r)$, which can be written as $n_f(r) = N_f \tilde{n}_f(r)$ and $n_c(r) = N_c \tilde{n}_c(r)$ where N_f and N_c are the number densities for the fine and coarse modes.

The size distribution for a two-mode scheme is

$$n(r) = n_f(r) + n_c(r) \qquad \text{with} \qquad N_0 = N_f + N_c \tag{4}$$

Although the size distributions of $n_f(r)$ and $n_c(r)$ are fixed, the two-mode size distribution $n(r)$ changes with different ratio of N_f/N_c. In climate models, the number density is not always an explicit input variable, but the mass concentration is. The mass concentration is defined as

$$m = \int \rho r^3 n(r)\,dr$$

where ρ is the density of dust aerosol. Assume the mass concentrations for the fine and coarse modes are m_f and m_c, the corresponding number densities for the fine and coarse modes can be obtained,

$$N_f = \frac{N_0}{1 + \frac{m_c}{m_f} R} \tag{5a}$$

$$N_c = \frac{N_0}{1 + \frac{m_f}{m_c}\frac{1}{R}} \tag{5b}$$