Effect of Cloud Water Content on the Atmospheric Extinction

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Abstract

The aerosol particles play an important role in the research of atmospheric radiation and climate change. In the process of calculating the radiative properties of aerosol particles, the complex refractive index is an important parameter. However, it can not be measured directly. Since the atmospheric aerosol is a particle system composed of various components in a wide range of sizes, the ‘Continental type’ of aerosol particles have been chosen in this paper, and the equivalent complex refractive indices of particles are calculated with Bruggeman mixing rule. The radiative properties of aerosol particles under different water contents are determined with Mie theory at the wavelength of 0.55 μm. The results show that the extinction coefficients and albedo increase with the increase in water content. When the water content in cloud is greater than 60%, the humidity becomes a dominant factor. The scattering of particles will increase as a result of the humidification in the atmosphere.

Keywords: Aerosol particles, radiative properties, effective medium theory, water content, complex refractive index

1. Introduction

In recent years, global climate change has become a scientific and social problem causing great concern. The factors that cause the climate change are various, including both natural factors (the solar radiation variations and volcanic eruptions, etc.), and human factors (such as greenhouse gases and the increasing aerosols in troposphere, etc.). Natural factors are beyond the control of human beings. Therefore, more attention has been paid to human factors [1]. There are evidences of an emerging pattern of climate response to forcing by aerosol particles [2]. This is going to be the central issues in this paper. Aerosol can be defined as the suspension of solid or liquid particles in the air. Tropospheric aerosols affect Earth’s radiative balance and climate through the direct effect of scattering and absorbing sunlight and indirect effect by changing the cloud albedo [2]. Although aerosol particles are also important in atmospheric chemical and physical fields, the radiative properties of aerosol particles in the atmosphere are mainly investigated in present study.

The complex refractive index is an important parameter in the process of calculating the radiative properties of aerosol particles. However, it can not be measured directly. Because aerosol particles are a mixture consisting of various components and needs to be taken as a whole component, the complex refractive index can be calculated with the help of some experimental data and a corresponding inverse model. For example, Jernings et al. [3] presented a method that took advantage of a transmittance spectrum to determine directly the absorptive index of the complex refractive index. Brewster and Kunitomo [4] used the KBr tablets transmissivity of coke particles to retrieve the dispersion parameters, then to gain the complex refractive index of coke particles. Felske and Ku [5] proposed a technique to determine the spectral refractive indices, size, and number density of soot particles from light scattering spectral extinction measurements in flames. Recently, Ruan [6] presented a technique for determining the optical constants of fly-ash particles from spectral transmittance measurements. Combined with the precise Mie theory and the Kramers-Kronig (K-K) relation, the complex refractive index
was estimated by the spectral transmittance distribution of a cloud of fly-ash particles in potassium bromide (KBr) pellets. Another way to obtain the complex refractive index is the effective medium theory (EMT) which can be employed to predict macroscopic dielectric properties for a material consisting of various components. Erlick [7] explored the range of visible refractive indices and single-scattering albedos that can be obtained using various mean field formulations for composite water and sulfate drops containing absorbing dust and soot inclusions. Voshchinnikov and Mathis [8] proposed a multi-layer sphere (MLS) model to account for porous, composite dust grains, and compared the MLS with EMT-Mie theory. Shen and Draine [9] investigated the scattering and absorption of light by random ballistic aggregates of spherical monomers with the analytical multi-layer sphere (MLS) model and effective medium theory (EMT), and compared with Discrete Dipole Approximation (DDA) results.

In the real atmosphere, the liquid water content has a great influence on the radiative properties of aerosol particles [10, 11]. It has been shown that the relative humidity has significant influence on the radioactive forcing effects of aerosol particles in the boundary layer near the ground [12, 13]. However, to the authors’ knowledge, little information about aerosol radiative properties with the change of water content can be found until recently. So the research emphasis of this paper also focuses on the influence of water content on radiative properties of the cloud.

In this paper, the equivalent complex refractive indices of 'Continental type' of aerosol particles are calculated by EMT. The radiative properties of aerosol particles in cloud with different water contents are studied by using Mie theory when they are homogeneously and non-homogeneously distributed in the cloud.

2. Basic theory

Effective Medium Theory is used to calculate the equivalent complex refractive index of medium doped with other mixture. Based on the mixed mode of different components, the various forms of effective medium theory formulas are developed, in which Maxwell-Garnett and Bruggeman theoretical formulas are commonly used. The Maxwell-Garnett mixing rule should be used for the case of many separated spherical inclusions randomly distributed throughout the particle, it is valid only when the volume fraction of inclusions are very small [14]. The Bruggeman rule has no such limitation, and it will be used to calculate the equivalent complex refractive indices of aerosols in this paper.

First of all, a brief introduction to Bruggeman rule is presented. The equivalent complex refractive index of the mixture can be calculated as a function of the constituent complex refractive index, their volume fractions, and possibly some other parameters characterizing the micro structure of the mixture. A full review of the theory and application of Bruggeman mixing rules can be found in texts dealing with effective medium approximations [14].

The Bruggeman mixing rule is defined as [14]

$$\sum_i f_i \frac{\varepsilon_i - \varepsilon_{av}}{\varepsilon_i + 2\varepsilon_{av}} = 0$$

(1)

where $\varepsilon_{av}$ is the mixture’s equivalent dielectric constant, $\varepsilon_i$ is the dielectric constant of each component of aerosols, and $f_i$ is the volume fraction of each component of aerosols.

In electromagnetic theory, the relationship between the dielectric constant $\varepsilon$ of non-magnet substance and the complex refractive index $m$ is as follow [14]:

$$\varepsilon = m^2$$

(2)

Where $\varepsilon = \varepsilon' + i\varepsilon''$ and $m = n + ik$, then the following relationship can be obtained [14]:

$$n^2 - k^2 = \varepsilon'$$

(3)

$$2nk = \varepsilon''$$

(4)

3. Results and discussion

3.1. Calculation of the refractive index of aerosol particles

According to the Standard Radiation Atmosphere (SRA) mode proposed by International Association of Meteorology and Atmospheric Physics (IAMAP) in 1983, aerosols can be divided into six categories according to their components: water-soluble particles, dust-like particles, maritime particles, soot, volcanic ash and 75% sulfuric acid. In the troposphere,
there are three types of aerosol mode composed of water-soluble particles, dust-like particles, maritime particles and soot particles with different volume percents, ‘Continental type’, ‘Urban-factory type’ and ‘Marine type’ [15], as shown in Table I.

**TABLE I. THREE TYPES OF AEROSOL MODE IN THE TROPOSPHERE**

| Composition        | Water-soluble | Dust-like | Maritime | Soot |
|--------------------|---------------|-----------|----------|------|
| Continental type   | 29            | 70        | 1        |      |
| Urban-factory type | 61            | 17        | 22       |      |
| Marine type        | 5             | 95        |          |      |

In this paper, we take ‘Continental type’ aerosols as an example, and use Bruggeman rule to calculate their equivalent complex refractive indices in different wavelengths. The complex refractive indices of water-soluble particles, dust-like particles and soot can be obtained in reference [15]. The results are shown in Table II.

**TABLE II. THE EQUIVALENT COMPLEX REFRACTIVE INDICES OF ‘CONTINENTAL TYPE’ AEROSOL PARTICLES**

| Wavelength (µm) | Continental type |
|-----------------|------------------|
|                 | Real part        | Imaginary part |
| 0.2             | 1.53             | 0.07283        |
| 0.25            | 1.531            | 0.03416        |
| 0.3             | 1.532            | 0.01244        |
| 0.337           | 1.532            | 0.01155        |
| 0.4             | 1.532            | 0.01145        |
| 0.488           | 1.532            | 0.01135        |
| 0.515           | 1.532            | 0.01135        |
| 0.55            | 1.532            | 0.01155        |
| 0.633           | 1.532            | 0.01145        |
| 0.694           | 1.532            | 0.01175        |
| 0.86            | 1.522            | 0.01318        |
| 1.06            | 1.523            | 0.01472        |

The influence of water content on radiative properties of aerosol particles can not be ignored in the real atmosphere. We use Bruggeman mixing rule to compute equivalent complex refractive indices of aerosol particles in different water contents at the wavelength of 0.55 µm. The results are shown in Table III. It can be seen from Table III that the real part and imaginary part decrease with the increase in the content of water.

**TABLE III. THE EQUIVALENT COMPLEX REFRACTIVE INDICES OF AEROSOL PARTICLES IN DIFFERENT WATER CONTENTS**

| Water content | Real part | Imaginary part |
|---------------|-----------|---------------|
| 100%          | 1.333     | 1.96E-9       |
| 80%           | 1.372     | 0.0022        |
| 60%           | 1.411     | 0.0045        |
| 40%           | 1.451     | 0.0068        |
| 20%           | 1.492     | 0.0092        |
| 0%            | 1.532     | 0.0115        |

3.2. Calculation of radiative properties of the cloud

According to the internal temperature and the phase state of cloud particles, cloud can be divided into the categories of water cloud, ice cloud and mixed cloud. In this paper, water cloud is taken for an example.

The content of cloud droplets plays an important role in the radiative properties of the cloud. The homogeneous and non-homogeneous distributions of cloud droplets content are discussed in the following parts.

1) Homogeneous distribution of cloud droplets in the cloud.

When cloud droplets are homogeneously distributed in the cloud, taking wavelength of 0.55 µm and particle size of 1 µm as an example, the radiative properties of a single cloud droplet with different water contents can be calculated by Mie theory. The results are shown in Table IV.

**TABLE IV. THE RADIATIVE PROPERTIES IN DIFFERENT WATER CONTENTS**

| Water content | Q_{abs} | Q_{sca} | Q_{ext} | ω  |
|---------------|--------|--------|--------|----|
| 100%          | 0.000000 | 3.944224 | 3.944224 | 1.000000 |
| 80%           | 0.055887 | 3.925065 | 3.925065 | 0.985961 |
| Water Content | $Q_{abs}$ | $Q_{sca}$ | $Q_{ext}$ | $\omega$ |
|--------------|----------|----------|----------|--------|
| 60%          | 0.113013 | 3.657981 | 3.770994 | 0.970031 |
| 40%          | 0.175648 | 3.268210 | 3.443858 | 0.948997 |
| 20%          | 0.262197 | 2.878895 | 3.141092 | 0.916527 |
| 0%           | 0.360452 | 2.535245 | 2.895696 | 0.875522 |

It can be seen from Table IV, the absorption factor ($Q_{abs}$) decreases with the increase of the water contents, while the scattering factor ($Q_{sca}$) will increase with the increase in the content of water. Overall, the extinction factor ($Q_{ext}$) and albedo ($\omega$) increase with an increase of the content of water.

2) Non-homogeneous distribution of cloud droplets in the cloud:

When cloud droplets are non-homogeneously distributed, the distribution file of cloud droplets is assumed to be the same as that of reference [16], which is shown in Fig. 1.

![Cloud droplets distribution of cloud (g/m3).](image1)

The distribution of cloud droplet sizes is also very important in determining the radiative properties of cloud. The gamma and lognormal distributions are commonly used. In this paper, lognormal distribution of cloud droplet sizes is chosen. It is assumed that the cloud droplets only consist of aerosol particles (the content of water in the cloud is 0%), then the extinction and albedo of cloud droplets are shown in Fig. 2 and Fig. 3.

![The extinction of cloud droplets without water (1/km).](image2)

From Fig.2 and Fig.3, the extinction and albedo increase with increase of droplet content in cloud.

The fact is that water droplets exist in the cloud, and the scattering of water is comparatively large in the visible range, it is necessary for investigating the influence of water contents on the cloud extinction. The radiative properties of aerosol particles in the cloud have been calculated with different water contents 40%, 60% and 80%, respectively. The extinction and albedo of cloud droplets are shown in Fig.4 and Fig.5.
As shown in Fig.4, the extinction of cloud droplets increases with the increase of water content. The maximum of extinction corresponds to the maximum cloud droplets content, and the scattering is strongest at the corresponding location.

From Fig.5, it can be seen that the albedo of cloud droplets also increases with the increase of water content. When water content is smaller than 60%, the absorption of cloud droplets cannot be ignored. However, when water content is greater than 60% (such as 80%), the albedo of cloud droplets is close to 1, which means there is almost no absorption and water becomes a dominant factor. The humidification will enhance the particles scattering in the real atmosphere. Meanwhile, the particles extinction increases with an increase in the humidification. Considering the extreme condition, the low visibility caused by fog is a good example.

4. Conclusion

In this paper, aerosol particles of ‘Continental type’ have been chosen in the investigation. The equivalent complex refractive indices of ‘Continental type’ aerosols and those of aerosols with different water content are obtained with Bruggeman mixing rule. The radiative properties of aerosol particles under different water content are studied by using Mie theory at the wavelength of 0.55μm. The results show that the extinction and albedo increase with an increase in the content.
of water. When water content is greater than 60%, the water will play a dominant role in the cloud. The humidification can enhance the particles scattering in the atmosphere.

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References

[1] G. Y. Shi, Atmospheric Radiation, 1st ed., Beijing: Science Press, 2007.
[2] Y. F. Cheng, Y. H. Zhang. An observation-based method for investigating the atmospheric aerosol radiative properties in PEARL RIVER DELTA of CHINA. Beijing: Science Press, 2008.
[3] S. G. Jennings, R. G. Pinnick, S. B. Gillespie, “Relation between Absorption Coefficient and Imaginary Index of Atmospheric Aerosol Constituents”, Applied Optics, vol. 18, 1979, pp. 1368-1371.
[4] M. Q. Brewster, T. Kunitomo, “The Radiative Properties of Particles in Fluidized-Bed Coal Combustion”, ASME J. of Heat Transfer, vol. 106, 1984, pp. 678-683.
[5] J. D. Felske, J. C. Ku, “A Technique for Determining the Spectral Refractive Indices, Size, and Number Density of Soot Particles from Light Scattering and Spectral Extinction Measurements in Flames”, Combustion and Flame, vol. 91, 1992, pp. 1-20.
[6] L. M. Ruan, H. Qi, W. An, H. P. Tan, “Inverse Radiation Problem for Determination of Optical Constant of Fly-ash Particles”, Int. J. of Thermophysics, vol. 28, 2007, pp. 1322-1341.
[7] C. Erlick, “Effective refractive indices of water and sulfate drops containing absorbing inclusions”. Journal of the Atmospheric Science, vol. 63, 2006, pp. 754-765.
[8] N. V. Voshchinnikov, V. B. Il’in, Th. Hening, D. N. Dubkova, “Dust extinction and absorption: the challenge of porous grains”, Astronomy & Astrophysics, vol. 445, 2006, pp. 167-177.
[9] Y. Shen, B. T. Draine, E. T. Johnson, “Modeling porous dust grains with ballistic aggregates, I. Geometry and optical properties”, The Astrophysical Journal, vol. 689, 2008, pp. 260-275.
[10] G. Hanel, “The properties of atmospheric aerosol particles as functions of the relative humidity at thermodynamic equilibrium with the surrounding moist air”. Advances in Geophysics. 1976, 19: 74-83
[11] M. Kocifaj, F. Kundračík, G. Videen. “Optical properties of single mixed-phase aerosol particles. Journal of Quantitative Spectroscopy & Radiative Transfer”. 2008, 109(11): 2108-2123
[12] M. Chin, P. Ginoux, S. Kinne, “Tropospheric aerosol optical thickness from the GOCART model and comparisons with satellite and Sun photometer measurements”, J. Atmos. Sci., vol. 59, 2002, pp. 461-483
[13] K. M. Markowicz, P. J. Flatau, P. K. Quinn, “Influence of relative humidity on aerosol radiative forcing: an ACE-Asia experiment perspective”, J. Geophys. Res., vol. 108 (D23), 8662
[14] A. H. Sihvola, “Electromagnetic mixing formulas and applications”, The institution of Electrical Engineers, London, vol. 6, 1999, pp. 154-162.
[15] H. Yin, Atmospheric Radiation Theoretical Basis, 1st ed., Beijing: Meteorology Press, 1993.
[16] K. F. Evans, “The spherical harmonics discrete ordinate method for three-dimensional atmospheric radiative transfer”, Journal of the Atmospheric Sciences, vol. 55, 1997, pp. 429-446.