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Numerical study of influence of different dispersed components of crystal cloud on transmission of radiant energy

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ABSTRACT

The calculated results of the transmission of visible and infrared radiation by an atmosphere layer involving ensembles of large preferentially oriented crystals and spherical particles are presented. To calculate extinction characteristics, the physical optics method and the Mie theory are applied. Among all atmospheric particles, both the small particles that are commensurable with the wavelength of the incident radiation and the large plates and the columns are distinguished by the most pronounced dependence of the transmission on spectra of radiant energy. The work illustrates features of influence of parameters of the particle size distribution, particle aspect ratios, orientation and particle refractive index, also polarization state of the incident radiation on the transmission. The predominant effect of the plates on the wavelength dependence of the transmission is shown. A separated and cooperative contributes of the large plates and the small volume shape particles to the common transmission by medium are considered.

1. Introduction

It is well known that crystal clouds affect the earth's radiation budget. The experts on climate change marked that the role of clouds in the atmosphere is one of the biggest uncertainties in predicting climate change today [1,2]. Study of effects of particle shape, sizes, optical properties, and orientation on propagation of the radiant energy is essential for understanding the role of crystal clouds in the transformation of the radiative fluxes [3]. The extinction is one of the values, which characterizes the transformed radiation. Determination of energy and polarization characteristics of the attenuation is the necessary link in the solution of many problems related to the investigation of the atmosphere by using the optical methods and also to studying the propagation of radiation in an aero-dispersed medium. For a full description of the radiation extinction, the extinction matrix (EM) is usually considered [4]. Elements (or combinations thereof) of the extinction matrix have been numerically calculated and discussed for various particles [5–10].

At present, by taking into account the particle orientation and the size distribution function as well as the polarization properties of the incident radiation of visible and IR range, the calculation of the extinction of radiant energy for an ensemble of semitransparent crystals is the actual solution for transmission problems. This solution provides results accurate enough for many applications such as the development of climate models, the study of the radiation propagation through anisotropic media, and the estimate of data of the laser and passive remote sensing of crystal clouds. The adequate numerical models are the basis for reliable interpretation of data of ice cloud sensing.

Clouds crystals are characterized by wide variety of particles with various shapes and size distribution functions. Particles that provide the wavelength dependence of the extinction are of greatest interest in investigation of the radiation transmission function (TF). Such objects are small (comparable with the wavelength of the incident radiation) particles and preferentially oriented large (particle size much larger than the wavelength) crystals that have plane-parallel faces [8,10]. For large crystals with violation of the parallelism of the faces of more than 10°, the extinction is determined by the effective area of shadow of particles and its concentration per unit volume, but it does not depend on the particle thickness and the radiation wavelength of the incident radiation.

To determine the optical characteristics of the transformed electromagnetic radiation by aerosol medium, which is presented as spherical particles, the Mie theory is usually used. The Mie solution for the scattered plane wave by a sphere is the universal technique [11]. This formalism can be used for simulation of scatterer having shape, which may be not only nearly spherical, but possesses a complex volume form. If the solution of the task requires an averaging over the particle's shape and orientation, or if account of features of the light-scattering characteristics, which are provided by a fine structure of crystals, is not significant, then

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application the Mie solution is quite acceptable. To take into account the role of non-sphericity and orientation of particles, it is necessary to use other techniques. At present, to calculate the light-scattering properties of non-spherical particles having arbitrary shape and orientation in space, the T-matrix procedure and the discrete dipole approximation (DDA) are effectively used [4,12]. The T-matrix method is based on numerical solutions of Maxwell's equations. The DDA considers the particle as a set of parts (dipoles) with subsequent application of solution of the electromagnetic volume integral equation. However, it is difficult to use these techniques for large particles with sizes that considerably exceed the incident radiation wavelength. A hybrid technique, which combines the geometric optics method and physical optics, provides acceptable results of calculating the characteristics of radiation transformed by large crystals. In the framework of this method, to calculate the properties of the radiation scattered by large particles with plane-parallel faces in the near-field zone, the beam-spitting technique is used opportunely. A special feature of this technique is a unity of all of reflected or refracted rays, which have the same direction of propagation, into beams of parallel rays [13]. For each beam with different orders of reflection from crystal faces, the phase shifts of wave are defined taking into account the thickness of the particle, the complex refractive index, the wavelength, and the direction of incident of the radiation on the crystal face. To determine characteristics of the near-field we used Snell's low and the Fresnel transmission and reflectance coefficients for the perpendicular and parallel components of a plane wave [6,13]. For large crystals, to determine the scattered radiation in the far-field zone, it is important to take into account a comparability of the diffraction field and the field of refracted beams passed through the crystal. A common approach in determining the diffracted and refracted fields allows summing them coherently; then the resultant field is well defined from near-field zone to far-field zone. To recalculate the field from near-field zone to far-field zone, the Fraunhofer integral is used. This approach allows us to improve the accuracy of calculations of the energy and polarization characteristics of the full forward-scattered field.

The task of this paper is to introduce basic regularities of the transmission of optical radiation by a layer of particles of different nature. We illustrate the influence of the small and large particles with different microphysical, optical, and orientation parameters on transmission by the layer of crystal cloud. This paper shows cooperative and separate effects of large and small particles on the wavelength dependence of the radiation extinction. Also the work illustrates when it should be consider a cooperative effect, and when it is sufficient to take into consideration only one component of the medium in estimation of the transmission and the extinction of radiant energy. Here we focus on analysis of calculated data of the transmission function for large crystals, which have the most number of poorly studied features. It is also demonstrated under which conditions it should be taken into account more accurate methods of calculating light scattering characteristics that consider the non-sphericity of small particles.

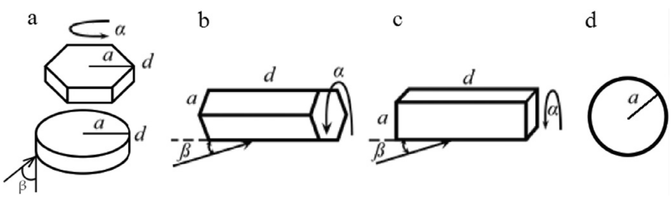

Fig. 1. Schematic representation of particles: circular and hexagonal plates (*a*); a hexagonal column (*b*); a rectangular column (*c*); a sphere (*d*).

2. Problem formulation

For numerical study of the properties of the transformed radiation passing through a polydisperse medium, let us consider large crystals having plane-parallel faces and small particles comparable to the wavelength of the incident radiation. The particles of these types produce the wavelength dependence of characteristics of the radiation extinction. The circular and hexagonal plates (Fig. 1*a*), the hexagonal column (Fig. 1*b*), the rectangular column (Fig. 1*c*), and also the spherical particle (Fig. 1*d*) are represented as models of scatterers. By a and d denote the geometric parameters of these particles as follows: (for the plates) a is the plate radius and d is the plate thickness; (for the columns) a is the side of the base of the column (it is considered the smallest face of the crystal) and d is the length of the column; (for the sphere) a is the sphere radius. The complex refractive index of particles is written as $\eta = n + i\ \chi$. The refractive index n characterizes the particle refraction and the absorption index χ quantifies the particle absorption. A position of the crystal with respect to the laboratory (Cartesian) coordinate system is described by the Euler angles (α, β, γ). The angle α defines the rotation of the plate (column) perpendicular to its basal face. The direction of propagation of an elliptically polarized plane wave with respect to the normal of the plane base is specified by the angle β, and the angle γ specifies the orientation of the polarization plane.

Let us consider a layer of an atmospheric medium containing particles. Optical radiation passes through the layer having thickness h. The transmission function of radiant energy for the homogeneous layer of the medium can be calculated using the formula as:

$$T = \exp(-\alpha_{ext} \cdot h), \tag{1}$$

where α_{ext} is the extinction coefficient. For the medium consisting of various disperse components, the total extinction coefficient is written in the following form:

$$\alpha_{ext} = \sum_{i=1}^{m} \alpha_{ext}^{i}, \tag{2}$$

where α_{ext}^{i} is the extinction coefficient for certain type of particles (for example, each type is characterized by the certain particles shape or the optical properties), here m is the total number of types of particles.

The extinction coefficient can be determined by an effective cross section of the extinction ($\langle \mathrm{S}_{\mathrm{ext}} \rangle$) based on the representation of particles with effective geometric and orientational parameters:

$$\alpha_{ext}^{i} = C \cdot \langle S_{ext} \rangle, \tag{3}$$

where C is the concentration of particles in unit volume.

For an ensemble of particles with the size distribution function N(a), the extinction coefficient can be written in an integral form. The integrand involves the extinction cross section ($\mathrm{S}_{\mathrm{ext}}$) for certain particles type:

$$\alpha_{ext}^{i} = \int_{a} S_{ext}(a) \cdot N(a)\, da\,. \tag{4}$$

The extinction cross-section for an individual particle can be written using (K_{1i}, $i = 1, 2, 3, 4$) the elements of the first line of the extinction matrix [4] as follows:

$$S_{ext} = K_{11} + K_{12}\frac{I_2}{I_1} + K_{13}\frac{I_3}{I_1} + K_{14}\frac{I_4}{I_1}, \tag{5}$$

where I_i ($i = 1, 2, 3, 4$) are the Stokes parameters of the incident radiation. To calculate the extinction cross-section for the plate, the hexagonal and rectangular columns, we used expressions obtained with the physical optics method [6,10]. Note, only the first three elements of the first line of the extinction matrix are significant.